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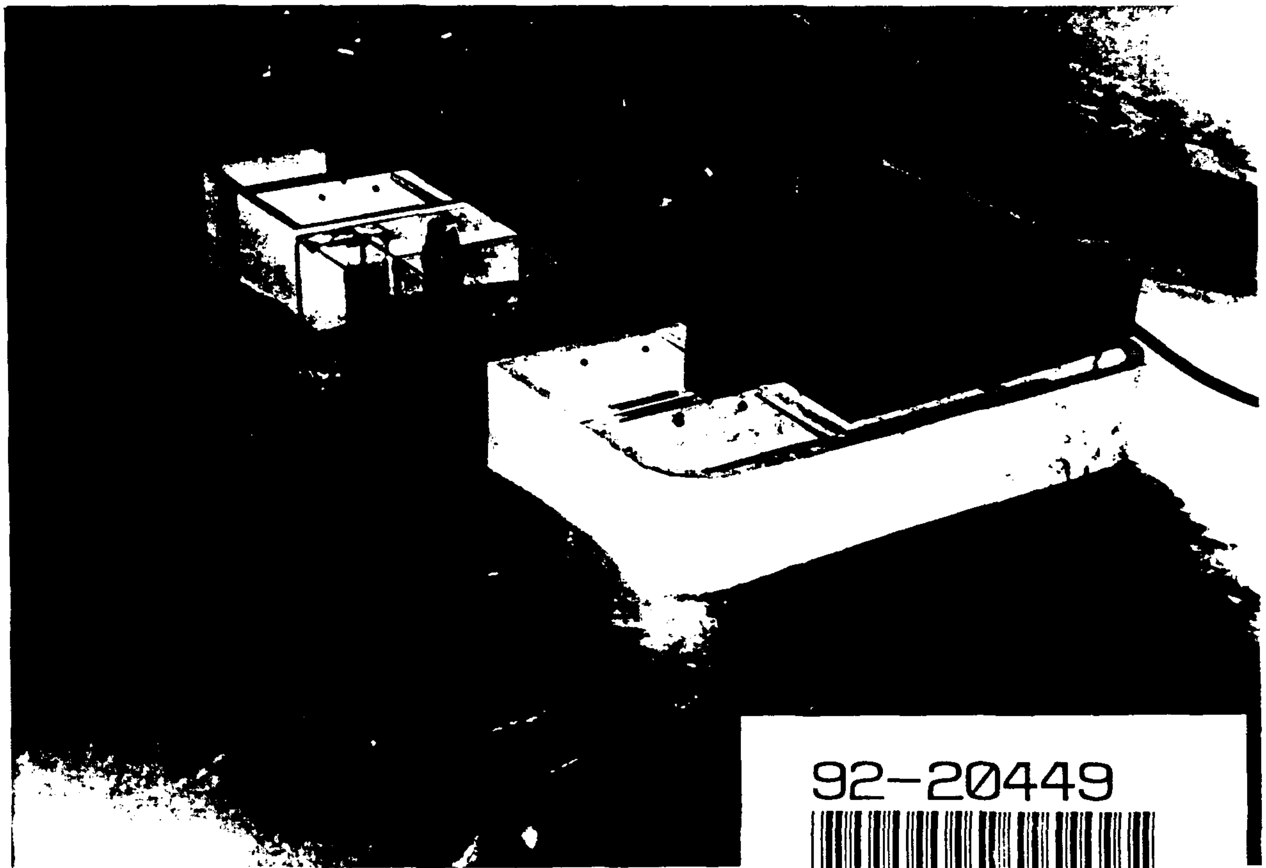
Research and Development Report

ACCIDENTAL OIL SPILLS DUE TO GROUNDING:

SUMMARY OF MODEL TEST RESULTS

BY GABOR KARAFIATH



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The International Maritime Organization (IMO) sponsored model tests to help in their evaluation of accidental oil spillage from a Mid-Deck Tanker (MDT) and from a Double Hull Tanker (DHT) Design. These tests were conducted at Tsukuba Institute, Japan, and at the Carderock Division, Naval Surface Warfare Center. The test results are explained herein and their significance is summarized.

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EXECUTIVE SUMMARY

The International Maritime Organization sponsored model tests at Tsukuba Institute, Japan, and at the David Taylor Model Basin, USA, in order to investigate the accidental oil spillage due to grounding of Mid-Deck Tanker designs and Double Hull Tanker designs. The Mid-Deck Tanker's horizontal division of the oil tankage reduces the hydrostatic oil pressure in the lower cargo oil tank to less than the ambient sea pressure and thus it is claimed that a puncture of the tank bottom results in sea water entering instead of oil exiting the tank. The Double Hull Tanker's advantage with regard to oil spill is the structural protection afforded by the inner hull and the claimed capability to capture some oil in the space between the inner and outer hull in the case of a grounding severe enough to cause a rupture of the inner hull.

The oil loss was assumed to be the sum of oil loss at the time of grounding plus the subsequent oil loss due to environmental effects such as tide, current and sea state. Models representing the oil tankage arrangement of one mid-deck design and of one double hull design were tested in order to estimate these oil losses under various conditions. This report summarizes and explains significant aspects of these model tests. The model test results were used by IMO in their evaluation of total oil loss from 6 Mid Deck and 12 Double Hull Tanker designs. The evaluation considered oil loss from grounding and collision.

The model tests with the Mid-Deck Tanker design showed that the Mid-Deck Tanker will lose some oil at the time of grounding and that this oil loss is dependent on the ship's initial speed and the damage hole size. In addition, subsequent environmental factors such as tide drop, current, and sea state can cause additional oil loss, and this loss is dependent on the severity of these environmental factors.

The model tests with the Double Hull Tanker design showed that the space between the inner and outer hull can capture oil that may be spilled from the main cargo tank. The effectiveness of these spaces in terms of retaining the oil is significantly influenced by the internal structure and oil tight subdivision of these spaces.

These model tests represent a technical first in the model testing of various tankage designs in order to determine accidental oil spill characteristics due to grounding. In the course of the testing, significant technical deficiencies in our understanding of the oil spill hydrodynamic phenomena were determined. A research program that would significantly increase our ability to predict the oil spill performance of various oil tankage designs and allow us to improve their oil spillage characteristics is presented.

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ABBREVIATIONS/TERMINOLOGY

DTMB	David Taylor Model Basin
MDT	Mid-Deck Tanker
DHT	Double Hull Tanker
IMO	International Maritime Organization
OTD	Oil Tanker Design (Committee)
VLCC	Very Large Crude Oil Carrier (Large Tanker)
CWC	Circulating Water Channel

ABSTRACT

The International Maritime Organization (IMO) sponsored model tests to help in their evaluation of accidental oil spillage from a Mid-Deck Tanker (MDT) and from a Double Hull Tanker (DHT) Design. These tests were conducted at Tsukuba Institute, Japan, and at the Carderock Division, Naval Surface Warfare Center. The test results are explained herein and their significance is summarized.

ADMINISTRATIVE INFORMATION

The David Taylor Research Center has been renamed, the new name is the Carderock Division, Naval Surface Warfare Center. Located at the Carderock site is the David Taylor Model Basin (DTMB) which is the name of the hydrodynamic testing facilities. In order to be consistent with past international usage, the tests conducted at this site will be referred to as the "David Taylor" tests or DTMB tests. Model tests conducted at the Ship and Ocean Foundation, Tsukuba Institute, Japan will be referred to as the Tsukuba tests.

This summary explaining the results of the oil spill model tests conducted at Tsukuba Institute and at DTMB was sponsored by the United States Coast Guard under Military Interdepartmental Purchase Request DTCG 23-92-HMF191. The conduct of the model tests, first tests at Tsukuba and the DTMB tests were sponsored by the International Maritime Organization. A second series of tests at Tsukuba were sponsored by the Japanese Ministry of Transport.

BACKGROUND

The IMO Steering Committee on Oil Tanker Design evaluated accidental oil spillage from several alternative oil tanker designs. Eighteen designs from various ship yards and ship designers were evaluated. Six of the designs were of the Mid-Deck Tanker (MDT) type and the twelve others were of the Double Hull Tanker (DHT) type. A typical midship section of the two tanker types along with that of a conventional tanker is shown in Figure 1. The distinguishing feature of the Mid-Deck type is the horizontal structure (deck) which divides the oil tankage into upper and lower tanks, hence the term Mid-Deck. The Double Hull Tanker has the feature that the oil cargo tank (inner hull) is separated from the outer hull, thus providing protection to the cargo tank. More detailed midship section

arrangements and ship characteristics of the 18 designs that were evaluated in reference 1 are shown in Figure 2A for Double Hull Tankers and Figure 2B for Mid-Deck Tankers. It can be seen that a large range of tanker sizes and a large variety of midship arrangements were investigated.

The IMO evaluated the oil outflow performance of these designs in the event of collision and grounding. The following effects related to grounding were considered:

1. Outflow occurring at the time of grounding. This has been termed the instantaneous exchange loss. It is determined by model tests.
   - For the MDT design, the critical issue is dynamic oil-water interaction near the rupture hole.
   - For the DHT design, the critical issue is the oil retention capability of double hull spaces.
2. Outflow due to tide drop; calculated analytically, demonstrated by limited model tests.
3. Outflow due to current; estimated from model test results.
4. Outflow due to sea state; estimated from model test result.
5. Outflow due to combined current and sea state; estimated from model test result.
6. Rupture and continue at speed estimated by model test, MDT design only.

The model testing was performed for two representative designs, the Double Hull Design 02-DH-280, the first design in Fig. 2A and the Mid-Deck Design 11-MH-280, the first design of Fig. 2B. These model test results were then generalized. The mid-deck model test results apply to all six mid-deck designs. The double hull model test results apply to all 12 double hull designs. The rupture and continue tests, item 6 above, represents a different grounding scenario and their results were for information purposes only.

EXPLANATION OF MID-DECK AND DOUBLE HULL DESIGNS

MID-DECK

The basic idea behind the Mid-Deck Tanker concept as shown in Fig. 1 is the horizontal separation of the cargo oil tank into upper and lower compartments. Thus, the static oil pressure at the bottom of each tank is reduced to approximately 1/2 that of the conventional tanker design. Thus, for the Mid-Deck Tanker, the oil pressure at the tank bottom is less than that of the ambient sea water and

a puncture of the tank bottom will result in water entering the cargo oil tank, see Fig. 3. For the conventional design, a puncture results in oil spilling to the sea because the oil pressure in the tank is greater than the sea water pressure. In both cases, there will be an oil loss due to turbulent mixing and agitation of the oil during the tank rupture and, in addition, some oil will be lost due to the flow of water past the rupture opening. This water flow may be due to the ship's own speed during the grounding or to ambient water current subsequent to a grounding.

It is common practice to fill tanks only 98% full in order to allow for the expansion of oil. Therefore, in the case of the Mid-Deck Tanker, the oil in the ruptured tank will float to the top of the tank and a small water layer will be found at the bottom. Not shown in Fig. 2 are small trunks or vents that connect each lower tank to the deck level. These trunks will also fill with oil subsequent to a rupture. The height of the water layer formed at the bottom is dependent on the excess volume of the tank prior to rupture (2% at the top and the trunk volume) and on the volume of oil lost at the time of the rupture. This water layer serves to reduce oil loss subsequent to the grounding that might be caused by sea state, current or tide drop.

For the conventional tanker, the oil will leak out until equilibrium is established. There will be a mixing and agitation of oil during the rupture, but the leaking out will predominate and control the oil loss. The top of the tank space will be filled with air. A small water layer may be established at the tank bottom if after grounding there is oil loss due to sea state or current.

DOUBLE HULL

The principal oil spill reducing feature of the double hull is that the cargo oil tank walls and bottom called the inner hull are separated from the outer hull which forms the outer skin of the ship. Thus, in a low energy grounding the outer hull can be punctured without puncturing the inner hull. Sea water will enter the space between the inner and outer hull but there will be no oil loss.

In the case of a high energy grounding, where both the inner and outer hull are punctured, oil will flow out of the cargo tank and sea water will flow into the space between the inner and outer hull. Figure 3 shows a case where some of the oil has flowed from the cargo tank into the space between the

inner and outer hulls and some of the oil spilled into the sea through the opening created by the puncturing rock. A water layer is formed and this water layer will help reduce further oil loss due to the action of sea state, current and tide. The extent of oil loss will depend on the dynamics of the oil, water and air flow in the double hull during rupture and on the arrangement of the double hull space with respect to subdivision and structural details that affect oil flow. And of course, the subsequent tide, current and sea state will affect the oil loss.

DESCRIPTION OF MODELS

It was impractical to construct a model of each of the 18 IMO designs under consideration. The 280,000 ton Double Hull and 280,000 ton Mid-Deck designs were selected as representative of Mid-Deck and Double Hull designs in general and models representing just the tankage portion of these designs were constructed. The portion that was modelled is shown in Figure 4. The models that were constructed are:

- 1/30 scale Mid-Deck Model
- 1/15 scale Mid-Deck Model
- 1/30 scale Double Hull Model

Each tankage model was made of clear plexiglass and had metal bow and stern fairings to guide the flow. Photographs and drawings are shown in Figs. 5 through 8. These models were first tested at Tsukuba and were then air freighted to DTMB.

A fourth model which was a duplicate of the 1/30 scale Mid-Deck Model was also constructed at Tsukuba so that additional testing could take place at Tsukuba without interfering with the DTMB tests. Detailed model descriptions are contained in the individual test reports.

The scale ratio of the models is established by the length dimension of the cargo tank that is modeled. At the time that model construction started, both the MDT and DHT 280,000 ton VLCC designs had a 54 m. ship beam and therefore the 1/30 scale MDT and DHT models were constructed to this design. Subsequently, the beam for both MDT and DHT designs were increased to 58 m, however, this change is not reflected in the models. Since the model tests results were generalized as a percentage of cargo oil lost from a given tank, this discrepancy in beam probably did not have a

significant effect on the oil loss assessment.

The 1/15 scale model is not a full beam representation but only consists of the lower and upper cargo tank. A 1/15 full beam model would have been too wide to test in the Tsukuba Circulating Water Channel (CWC) test facility, therefore, a model representing only a cargo tank was built. Even so the designers of the 1/15 model elected to make it only 70% of the width of the cargo oil tank in order to avoid interference with the Tsukuba CWC walls. This decision to make the 1/15 model have a different geometry than the 1/30 model, (all dimensions are not in 2 to 1 proportion), makes the interpretation and comparison of oil loss data from the two models very difficult because the cause of any oil loss differences, scale effect or geometry difference, is not known for sure. Note: The Tsukuba CWC is only about 1/2 the width of the DTMB CWC.

All of the models were fitted with simple bow and stern fairings.

ASSUMED GROUNDING SCENARIO

The model tests were designed to help establish oil loss for the following grounding scenario.

1. Tanker hits the ground and comes to a halt in a relatively short time. Depending on the initial velocity, ground conditions and the structural strength of the tanker, the tanker will come to a halt in less than 1 minute. During this time some initial oil may be lost and this oil loss is called instantaneous exchange loss. The instantaneous exchange loss was estimated from the "rupture and stop" model tests for the MDT designs. For the DHT designs, this loss was evaluated at zero forward speed during the rupture tests.
2. Subsequent to the grounding, environmental conditions may cause additional oil loss. These conditions are:

   - Current
   - Sea state
   - Tide drop

   Model tests on the MDT designs were conducted to assess the loss due to current and to sea state acting in combination and also acting individually. Tide drop model tests were also conducted, however, the tide drop effect could just as well have been calculated. Tide drop occurs relatively

slowly, approximately 6 hours between maximum high and low tide, and dynamic flow effects should be minimal.

Thus, the general expression for oil loss due to grounding is:

OIL LOSS DUE TO GROUNDING	=	OIL LOSS AT TIME OF GROUNDING (instantaneous exchange)	+	SUBSEQUENT OIL LOSS DUE TO ENVIRONMENT (tide, current, sea state)

The oil loss at the time of grounding has been called the instantaneous exchange loss. The subsequent environmental losses are due to the effects of tide, current, and sea state. The magnitude of the instantaneous exchange loss will in general have an effect on subsequent oil losses.

3. An alternative scenario, rupture and continue, was also tested for the MDT. In this scenario, the tanker bottom is punctured by a sharp protruding rock and some initial oil is lost. Due to the large size of the tanker, the puncture is not detected and the tanker continues steaming at speed. Additional oil is lost due to the forward speed of the tanker.

FACTORS AFFECTING OIL OUTFLOW

Prior to the model tests, it was recognized that the following factors would have an effect on the quantity of oil spilled due to grounding. The importance of each factor may vary depending on the design.

- Static Pressure: The oil static pressure in the tank relative to the external water static pressure is probably the most important determinant of oil loss. Figure 1 shows the relative static pressure of oil and water for the different tanker types. These pressures are dependent on ship draft and the height of oil in the cargo tank.
- Extent of Damage: Ship repair data were examined by the OTD Steering Committee to guide the selection of a "typical" damaged hole. These data more accurately reflect the extent of ship structure that needs repair subsequent to a grounding rather than the size of hole resulting from the grounding. Nevertheless, a maximum hole size and width were provided by the OTD Steering Committee for guidance and the models were tested with several hole sizes up to the maximum size.

- Ship Speed at Time of Impact: This speed will not only influence the extent of damage, but will also cause oil loss due to water flowing past already ruptured bottom plating while the ship is coming to a halt.
- Current: A current past a ruptured tank was envisioned to be a possible cause for oil loss above and beyond the oil lost initially at the time of grounding. There are currents in the ocean and ports of the world. Initial model testing guidance was to include currents up to 7 knots. However, based on an estimate of likely current to be expected, the final guidance was to evaluate oil loss in a 3.5 knot current.
- Sea State: The action of the waves will cause the ship to move and will also cause some pressure fluctuation in the water near the damaged hole. The OTD Steering Committee's concern was with regard to the up and down movement of the damaged cargo tank causing a pumping action that induced additional oil loss.
- Tide Drop: If subsequent to a grounding the tide drops, there will be less static water pressure at the bottom of a damaged cargo tank. This drop in pressure may allow additional oil to leak out. Initial guidance was to test for a maximum tide drop of 10 meters, however, later it was recognized that 10 meters was extreme. The final tide drop guidance is 6 meters and, as a point of reference, 6 meter tides are common in some Alaskan waters.

SUMMARY OF MODEL TESTING

All of the model tests were conducted with mid-deck or double hull models. A conventional tanker design was not tested because the purpose of the model tests was to help in the evaluation of oil outflow due to grounding between mid-deck and double hull.

In all of the testing, it was assumed that the upper tankage of the mid-deck design is not breached as a result of a grounding. The following tables summarize the extent of the model tests.

TSUKUBA TESTS OCT-NOV 1991

SHIP CONFIGURATION	TEST TYPE, CAUSE OF OIL LOSS	CONDITIONS
MDT	Current only	- 3 to 7 knots - hole size varied - longitudinal and transverse model orientation - water layer varied
	Ship motion caused by waves	- No current
	Current and ship motion	- Orientation varied - 3&5 knot current
	Tide drop test	- zero current
DHT	Tide drop test	- "J" type ballast tank, zero current
	Rupture test, zero speed	- Double hull space unintentionally flooded, "J" type ballast tank

The documentation of these tests is in references 2, 3, and 4.
Note: 1 knot = 1.15 miles per hour

DTMB TESTS DEC 1991-FEB 1992

SHIP CONFIGURATION	TEST TYPE, CAUSE OF OIL LOSS	COMMENTS
MDT	Current only	- 3&5 knots, vary water layer - one reduced draft condition
	Oscillation only	- zero water layer
	Current & oscillation	- 5 kts, zero water layer
	Tide drop	- zero current
	Rupture & stop	- 5, 10, 7 1/2 & 14 knot initial speed - reduced draft - partial load test - vary hole width - vary current deceleration
	Rupture & continue	- 10 knots continuous speed - 1&2 hr. ship operation
DHT	Rupture, zero speed	- "U" type ballast tank - no blockage of rupture hole - 50% blockage (by rock) of rupture hole

The documentation of these tests is in references 5, 6, and 7.

TSUKUBA TESTS JAN 1992

SHIP CONFIGURATION	TEST TYPE, CAUSE OF OIL LOSS	COMMENTS
MDT	Rupture & stop	- 5, 7 1/2, 10, & 15 knot speeds - rupture hole width variation - rupture hole length variation - variation in simulating the rupturing rock - partial load test
	Rupture & continue	- 10 kts - hole width variation - 2 hr ship operation

The documentation of these tests is in references 8 and 9.

SIGNIFICANT FINDINGS FROM MODEL TEST DATA

EFFECT OF CURRENT - MDT

The October Tsukuba tests showed that the velocity of the current has a very strong influence on the oil loss. Figure 9 from reference 8 shows the predicted oil loss as a function of elapsed time (ship scale) for various current velocities. This figure is based on the 1/15 model which had the reduced tank width and carried proportionally less oil than the 1/30 model. The percentage oil loss shown on the figure is the ratio of lost oil to the lower cargo tank volume, 8336 m^3. The lower cargo tank is the only damaged tank. The original figure showed a percentage based on 29,650 m^3, the approximate volume of upper and lower tanks both port and starboard. The percentage oil loss after 2 hours is very significant (10-20%) for the 5&7 knot current condition, however, it is small, about 1% for the 3 knot current. During final deliberations regarding a realistic current speed, the OTD Steering Committee decided on 3.5 knots.

The initial model condition for these tests consisted of an open damage hole and a quantity of oil in the "damaged" tank corresponding to either 300, 600, or 900 mm ship water layer. The CWC was then turned on until the desired current was achieved and after a specified time the current was stopped and the remaining oil levels in the tank were measured and oil loss was calculated.

The design condition for this test was 600 mm water layer corresponding to an oil tank 98% full. The DTMB tests conducted only at the 3 and 5 knot, 600 mm, conditions, repeated the Tsukuba oil

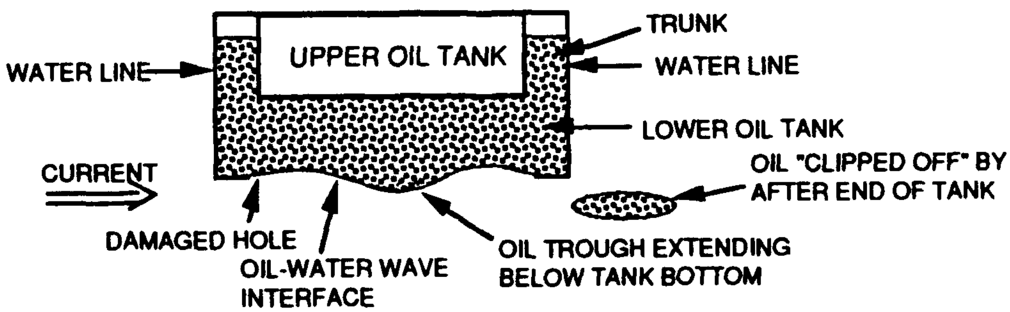
loss within experimental accuracy.

The model test agenda for Fig. 9 was designed to quantify the oil loss due to an external current subsequent to a grounding. At this time, proponents of the MDT design argued that since the sea water pressure was greater than the oil pressure inside the cargo tank, very little or no oil would result at the time of rupture. However, the very steep rise in oil loss at the 7 knot current condition combined with possible dynamic effects during the rupturing process, led to suggestions that oil might be lost at the time of rupture. The "current' in this case would be the water flow past the hull, generated by the tanker's forward speed. The oil in the damaged cargo tank is influenced by this flow during the short period of time that the tanker decelerates from it's initial speed to a complete stop at the conclusion of the grounding. This oil loss will be discussed under the "rupture test" heading later in the report.

Figure 9 shows that the oil loss due to current tends to reach a limiting value after 2 hours ship operation. Additional model tests at DTMB for slightly different loading conditions were carried out for a duration corresponding to 7 hours elapsed time (ship scale). The oil loss was still increasing with time, albeit slowly when the tests were terminated at the 7 hour point.

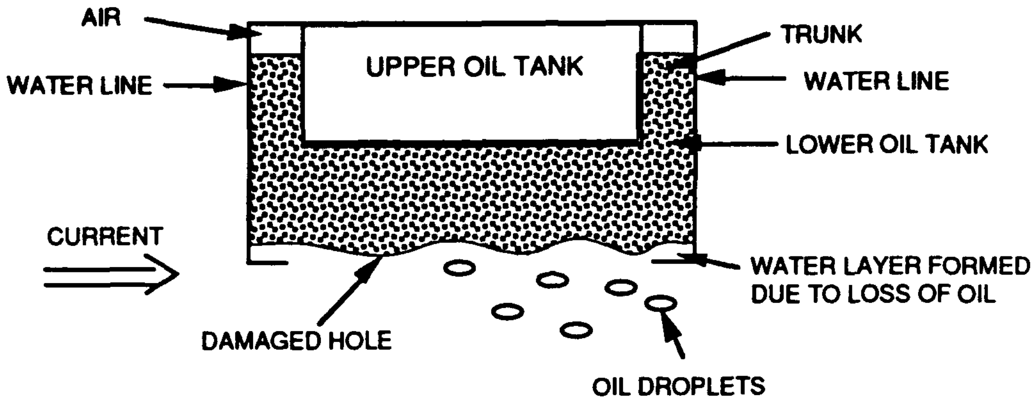
The physical phenomena associated with oil loss due to current was observed at DTMB to be the following: 1) At first a relatively large wave system is formed at the interface between the oil at the tank bottom and the ambient water. These waves travel longitudinally back and forth in a periodic fashion. The large amplitude oil troughs of these waves extend beyond the bottom of the tank and as these troughs approach the rear of the damage hole, the oil is clipped off and carried away by the current as shown below.

PROFILE VIEW OF TANK



A relatively large volume of oil, possibly 60 to 80% of the total oil loss, is lost quickly by this mechanism. Video tapes showing this phenomena are available.

As the oil is lost, it is replaced by water and the water layer increases in the tank. The amplitude of the waves appear to be diminished and the wave trough no longer projects below the tank bottom.



At this point, the principal oil loss mechanism is by the formation of oil droplets that are swept out of the hole by the moving water.

This complex oil loss mechanism that appears to change with the extent of the water layer and the amount of oil lost causes a difficulty in extrapolation of model test data to full scale predicted oil loss. This will be further discussed under the further in the section on the prediction of oil loss from model test data. This observation of oil loss is also consistent with the large initial oil loss and the subsequent tapering off with time.

EFFECT OF SHIP MOTION - MDT

Analytical estimates of the heaving motion of a ship in a given sea state were prepared by Mitsubishi Ltd. and the MDT models were tested both at Tsukuba and at DTMB to estimate the oil loss. The model test procedure was to oscillate the model in a manner that simulated the motion of the oil tank in the ship. In Tsukuba, the oscillation was manually induced and resulted in a pitching motion with a period near, but not at the desired period. At DTMB, the oscillation was mechanically controlled and the desired pure heave at the proper heave period was obtained. However, at DTMB,

the tests were at zero water layer, an limiting condition for the MDT, which was not the design condition. This limiting condition was requested by the sponsor.

At both facilities, the oil loss due to oscillation alone (zero current) was very small. The reason for this, as observed at DTMB was that the oil that was lost on an upward oscillation was recaptured on the downward oscillation.

EFFECT OF CURRENT AND SHIP MOTION - MDT

The combined effect of current and ship motion was also tested at both Tsukuba and DTMB. The effect of the current was to sweep away the oil that emerged from the tank on the upward oscillation and very little oil was recaptured on the downward oscillation. Thus, in the presence of current, oscillation increased the oil loss. This is shown in Fig. 10 where the higher Beaufort number corresponds to a larger sea state and a larger oscillation.

The Beaufort Scale shown in Fig. 10 represents a wind speed. Associated with this wind speed is a range of wave heights and lengths that arise in open sea after the wind has been blowing for a long time. The Beaufort 8 condition is a fresh gale, wind speeds 34 to 40 knots average wave height 13 to 18 feet. The difference in the DTMB and Tsukuba data is probably due to differences in oscillation excitation and most importantly to the initial water layer, zero for DTMB and 600 mm for Tsukuba. The Tsukuba data represents the design condition for the MDT.

The important result with regard to oil loss due to oscillation as shown in Fig. 10 is that sea state will significantly increase the oil loss due to current. Compare the BF 0 and BF 8 data. At 3 knots current, the oil loss more than doubles (although it is still small) and at 5 knots current the oil loss is increased by 60 to 80%.

EFFECT OF DAMAGED HOLE ORIENTATION - MDT

Figure 10 also shows data with the model tested longitudinally and transversely relative to the current. Surprisingly there was very little difference in the oil loss. As a consequence of this result, all

subsequent tests at DTMB and Tsukuba were conducted with the damaged hole aligned with the current.

A possible explanation for the relative insensitivity of oil loss due to model orientation relative to current may lie in the fact that each tank is subdivided by internal non-oil tight bulkheads which provide structural support. Thus, the longitudinal fluid movement in the damaged hole is somewhat restricted by the internal tank structure and the hole orientation to the flow becomes less critical.

RUPTURE AND STOP - MDT

These tests were conducted at DTMB and at Tsukuba (Jan 1992). Unlike previous testing in a current where the damaged hole in the model was already open, these tests started with a fully oil tight model and simulated a rupturing of the tank and the deceleration of the tanker to zero speed.

The rupturing mechanism at DTMB was a set of sharp steel prongs that were moved upward to puncture a very thin plastic sheet that covered the predefined damaged hole. The prongs were then slid aft to slice open the plastic completely.

At Tsukuba, the rupturing mechanism consisted of a plastic sliding door that covered the prepared opening. This door was oil tight when closed.

In both facilities, the model was held stationary and the current was decelerated to simulate ship stopping whereas in the real case the water is stationary and the ship decelerates to zero speed. In both facilities, the deceleration of the water was accomplished by shutting the power to the Circulating Water Channel drive motors and letting the water current come to a stop. Neither facility was able to make the water current stop quickly enough, however, DTMB was able to perform a quick stop test (see Fig. 11) for which the current slowed to 3 knots in less than 2 minutes (ship scale).

The tests were conducted with various methods of simulating the puncturing rock and at an additional partial load condition. These results are discussed in the test reports. They did not affect the final oil loss evaluations and are not discussed here.

The oil loss data from DTMB and Tsukuba are shown in Fig. 11. Agreement is generally good considering the different facilities, current deceleration rates, different puncturing methods between

the two facilities. The corresponding water layer that existed subsequent to the test is shown in Fig. 12. The loading condition represented by this water layer must be the starting point for assessing additional oil loss due to tide, current tor sea state.

The oil loss of Fig. 11 is for one tank only. The speed shown is the initial rupture speed. The oil loss from the forward most tank that is ruptured could be directly estimated from this curve. The second tank that is ruptured will be a small period of time later at a slower initial speed due to the slowing of the ship during the rupturing of the first tank. Each successive tank that is ruptured will be at a slower initial speed. This is shown in reference 9 and reproduced here as Fig. 13. The oil loss is based on the Tsukuba data as reinforced by the DTMB quick stop data. The average oil loss for all tanks was calculated because the oil loss evaluation computer code for the 18 original designs required an average oil loss input. The initial steering group assumption of 1% loss due to rupture and stop (initial exchange loss) was not too different from the 1.2% average shown in Fig. 13 and therefore the initial oil loss calculations did not have to be modified.

The average oil loss is sensitive to the ship speed at the time of impact. Fig. 13 is for 10 knots initial speed. The extrapolation of Fig. 13 can be used to estimate the sensitivity of the oil loss to initial ship speed. Fig. 14 shows this extrapolation. Note that at 15 knots, the initial exchange loss is about 5 times the loss at 10 knots. Thus, it can be seen that the assumed initial ship speed is very critical to the magnitude of the loss. The OTD Steering Committee assumed the loss at 10 knots ship speed.

The spots shown in Fig. 14 correspond to 3, 4, 5, and 6 damaged cargo tanks. At 15 knots, the entire bottom of the ship is damaged. Remember that there are six cargo tanks arranged longitudinally. Additional structural analysis, possibly testing, might be needed to confirm the method of predicting crack length that is inherent to the prediction of Fig. 13 and subsequently affecting Fig. 14.

RUPTURE TESTS - DHT WITH "J" TANKS AND "U" TANKS

Rupture tests were conducted on the Double Hull Model in order to assess the oil loss that occurs at the time of grounding. However, unlike the MDT rupture tests, all rupture tests with the DHT model were at zero forward speed.

In the DHT rupture tests, the principal objective was to discover what happens to the oil that leaves the cargo tank. Is it going to be captured in the space between the inner and the outer hull or will it be lost to the sea?

Rupture Tests With "J Tanks"

The first rupture test was conducted in Tsukuba. The DHT tank configuration was a "J Tank" configuration as shown in Fig. 15. Normally on a tanker, a large portion of the space between the inner and outer hull is used for ballast tanks. When the cargo oil tanks are empty, the ballast tanks are filled with water in order to ensure a minimum mean draft for seaworthiness, however, when the cargo oil tanks are full, the ballast tanks are empty. Thus, it was the intention at the time of the Tsukuba model tests to have the "J Tank" empty (i.e., air filled). Due to difficulties with the model leaking, the following test was performed instead:

1. "J Tank" was allowed to flood.
2. A tide drop of 1.7 meters was simulated by allowing the water level to drop.
3. With the outer bottom hole open, inner bottom rupture was simulated by pulling open a small sliding door.

The resultant oil loss is shown in Fig. 16 labelled DHT "J" Tank Tsukuba Test. The video of this test shows a high velocity plume of oil exiting downward in a jet from the cargo tank, through the stagnant water in the "J Tank" and finally to the outside sea through the already breached outer hull opening. The oil retained in the "J Tank" was about 14% of the oil exiting the cargo tank. The ruptured hole size in this case was very small 0.45 x 4.5 m ship scale and the small hole size along with the 1.7 m tide drop may have contributed to the "jet-like" characteristic of the outflow.

Rupture Tests With "U Tanks"

Subsequent to the Tsukuba tests, IMO directed DTMB to conduct similar tests except that a "U Tank" configuration (shown in Fig. 15) should be used and that the puncture of the inner and outer hull should be simultaneous. There was to be no water in the "U Tank" prior to the test and a case where the puncturing rock blocks some of the outer hole was to be done. The outer hull hole size was

specified as the same size, 37.5 m x 3.75 m as for the MDT rupture tests. The inner hull rupture hole was half the width of the outer hull hole.

These tests were conducted at DTMB with the specified damaged hole sizes covered by a thin plastic sheet that was subsequently punctured from below by a set of sharp steel prongs and wires interconnecting the prongs. For the blockage case, a wooden body representing a rock blocked 50% of the outer hull hole area.

The oil loss results are shown in Fig. 16. For the no blockage case, the oil lost to sea is 6.2% of the damaged cargo oil tank volume which is 19,945 m^3. The model test results apply to the zero tide drop point. The subsequent oil loss at 7.7 and 8.7 meters tide drop was obtained by calculation.

The "U Tanks" were much more effective in capturing the oil exiting the cargo tank than the "J Tanks". For the no blockage case, 76% of the oil leaving the cargo tank was captured by the "U Tank". Some of the differences in effectiveness between "J" and "U" tanks capability to capture oil was due to the differences in testing procedures, however, it is felt that the "U Tanks" are far superior in terms of capturing the oil because they provide more volume for the oil to occupy. The "U Tanks" will also have a greater resultant water layer and provide greater resistance to oil loss due to current, sea state, and further tide drop.

Also, shown in Fig. 16 is the MDT tide drop data from Tsukuba. This oil loss does not include the initial exchange loss.

The selection of "U" or "J" tanks or a combination of the two for a particular ship design must primarily consider the impact of tank type on the ships static upright stability while in a damaged condition. Nevertheless, reference 10 indicates that there are successful designs with "U Tanks".

The internal structural details in the ballast tanks will also play an important role with regard to the amount of oil recaptured by the tanks. Figure 7 shows the hole area, i.e. open passage area for oil to flow through, that was drilled through the structural bulkheads to form the "U Tank". The holes were at the top and bottom of the bulkheads. The total hole area was 6.5 percent of the total bulkhead area. It is felt that larger holes could be provided without affecting the structural integrity of the

bulkhead. Figure 17 shows typical structural details of double hull designs. Note that the lightening holes are placed at mid level in the ballast tank space. Figure 17 shows lightening holes in transverse bulkheads, and the holes in longitudinal bulkheads would be similar. From an oil spill prevention point of view, it might be desirable to locate the holes at the top and at the bottom of the longitudinal bulkheads in a "U" or "J" tank. This design aspect requires further investigation.

PARTIAL LOAD TESTING - MDT

When the Mid-Deck model was tested during the rupture tests with the cargo oil only 50% full, several observations were noted which are of importance relative to the design of such a ship. First of all, the oil in the tank experienced a violent motion that resulted in oil splattering up the vent trunks clear to the top deck. It would be prudent to estimate the forces that such violent motion of the oil cargo causes in order to ensure adequate structural strength. Secondly, agitation in the vent trunks was observed for quite some time after the rupture was over. Oil bubbles, some quite large, kept coming through the oil free surface in the vent trunk. Note, that the cargo oil tank (Fig. 8) is subdivided into seven compartments by six non-oil light transverse bulkheads that provide structural support. There were small holes that allowed fluid passage at the top of each bulkhead. There are seven compartments, but only two vent trunks. At the time of rupture, oil forces air upward through each compartment and the air pockets from each compartment migrate to the ends of the cargo tank where the vent trunks are located. It is felt that the small size openings at the top of the bulkheads restricted the passage of air, not to mention oil. The size of the hole needed should be a subject for further study. Thirdly, the tank was 50% full but experienced only 1/6 the oil loss of a full tank. The large cushion of air in the tank may have had a significant effect on this decrease in oil loss. It would be of interest to test the MDT at slightly greater air layer than the 2% associated with the 98% full tank to see if oil loss could be reduced, i.e., the test should be perhaps at 95% full capacity. Conversely, rupture tests should be conducted at 100% full oil capacity to determine oil loss in case the tank is accidentally overloaded or if an unusual amount of expansion takes place.

RUPTURE AND CONTINUE AT SPEED TEST

The ship scenario for the rupture and continue at speed test is that the ship runs over a jagged rock or other sharp object like a pipe and the cargo tank is slit open. The damage is not immediately noticed and the ship continues at speed for some time.

These tests were conducted both at Tsukuba and at DTMB with the 1/30 scale MDT model. The ship speed was 10 knots in both cases. In Tsukuba, the rupture was simulated by a sliding door, at DTMB it was simulated by puncturing a thin plastic membrane with prongs from below. The oil loss predictions are shown in Fig. 18. This difference in the rupturing mechanism probably accounts for the higher oil loss shown by the Tsukuba test. After rupturing, the hole in the Tsukuba test had well defined edges whereas the DTMB model hole had torn pieces of plastic fluttering in the hole. The question of which opening is more realistic is not resolved. The torn plastic in the DTMB test could be simulating jagged pieces of hull plating, whereas, the Tsukuba test represents a rupture with well defined straight edges.

The 8% oil loss shown by the Tsukuba rupture and continue test is large in relation to other types of oil loss such as approximately 3% oil loss shown by the rupture and stop test. This rupture and continue test was for information purposes only and was not used in the overall oil loss assessment.

PREDICTION OF SHIP OIL LOSS FROM MODEL TEST DATA

BASIC SHIP-MODEL RELATIONSHIPS

The model to ship length relationship is given by the linear scale factor λ. Thus,

$$\text{Length (ship)} = \lambda \cdot \text{Length (model)}.$$

For the oil loss tests, the characteristics length is the cargo tank length and therefore,

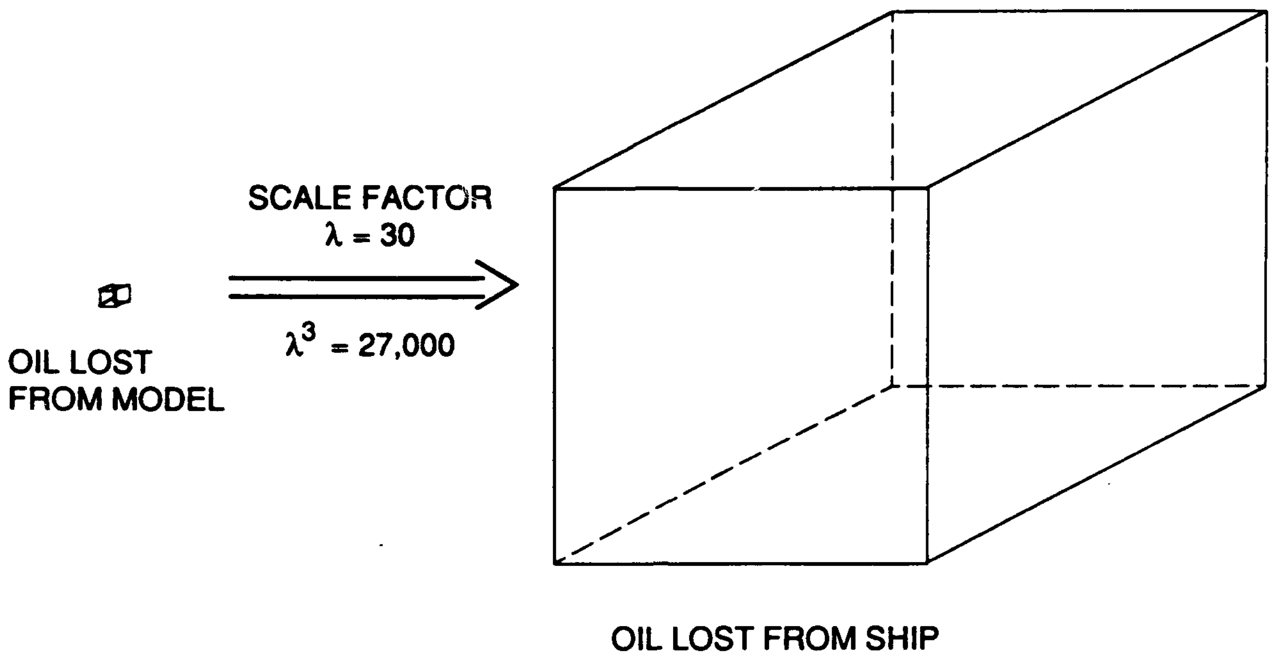
$$\text{Cargo Tank Volume (ship)} = \lambda^3 \text{ Cargo Tank Volume(model)}.$$

It follows that the oil lost is given by:

$$\text{Volume oil lost (ship)} = \lambda^3 \text{ Volume oil lost (model)}.$$

For a scale factor $\lambda = 30$ the graphic comparison of model and ship oil lost is shown below.

GRAPHIC COMPARISON OF OIL LOSS RELATIONSHIP
BETWEEN MODEL AND SHIP



Thus, because of the 27,000 fold extrapolation of the model oil loss, it becomes very important to ensure that the oil loss at model scale is caused by the same hydrodynamic physical phenomena that cause oil loss at the ship size. However, it is not possible to correctly represent in one model test all of the different kinds of forces acting on a fluid particle. Some of these forces include:

- static pressure forces
- inertial forces (mass x acceleration)
- viscous forces
- surface tension forces

The assumption of a linear scale factor and the Froude scaling law used in these tests allowed the static pressure forces and the inertial forces to be correctly represented during the oil spill model tests. The effects of not being able to properly represent viscous forces and surface tension forces were neglected. See Appendix A for a more complete discussion of forces acting on a fluid particle and how these forces should be represented in model tests.

It should be noted that many types of model tests a.e in this situation of not being able to correctly represent all the forces acting on the fluid particle. However, for many model tests, such as resistance

and powering tests, correction procedures have been developed to account for the fact that the viscous forces are not correctly represented during the test. Comparisons with full scale data are used to verify these correction procedures. The oil spill model testing, however, is relatively new and there are no established procedures for correcting the model data to account for the effects of viscosity and surface tension. Furthermore, there have been no comparisons of model test predictions to full scale data.

SCALE EFFECT

The first set of oil loss experiments were conducted at Tsukuba, where it was decided to conduct Froude scaled model tests. In order to be consistent, all subsequent testing, including the DTMB tests, were also conducted according to Froude scaling. Because there was uncertainty regarding the Froude scaled test, (i.e. model speed = ship speed $/\sqrt{\lambda}$) two models of the mid deck tanker, a 1/15 and 1/30 scale model were constructed and tested. It was hoped that both models would give the same predicted oil loss and thus allay concerns regarding the prediction accuracy.

Because of the limited width of the Tsukuba test facility, the larger, 1/15 scale model was built with a reduced width cargo tank. For details, see the model description section of this report. Thus, the two models are not geometrically similar and this geometric dissimilarity leads to difficulty in interpreting the oil loss results. Are differences in oil loss due to scale effect or model geometry differences?

Figure 19 shows the oil loss prediction from the two models. The following table shows the same data in tabular form.

Time	Oil Loss m^3 1/30 model	Oil Loss m^3 1/15 model	Oil Loss Ratio 1/30 ÷ 1/15
1 hr	1200	760	1.58
2 hr	1300	940	1.38
7 hr	1470	1310	1.12

Remember that in relative terms, the 1/30 model carries approximately 33% more oil than the 1/15 model. Thus, in the absence of scale effect, one would expect the oil loss ratio to stabilize at a value near 1.33 after a sufficient time has elapsed. This is not the case. After 7 hours, the oil loss ratio is 1.12 and the trend is that it will decrease with additional time. By inference from the above

consideration, it is clear that there is some model scale effect that is not properly accounted for in the extrapolation of oil loss from model tests where the velocity is Froude scaled. The exact magnitude of this scale effect can not be defined because of the differences in model geometry between the 1/30 and 1/15 model. The above noted scale effect will introduce an error or uncertainty in the oil loss prediction for the MDT design. The prediction of oil loss in the following conditions will be affected.

1. oil loss due to current;
2. instantaneous exchange loss, i.e. puncture and stop test
3. oil loss due to ship speed, i.e. puncture and continue test

Note that the discrepancy in oil loss as shown in Fig. 19 is greatest at the small value of elapsed time. Thus, predictions from the instantaneous exchange loss tests will be affected. The instantaneous exchange loss tests were for the most part conducted at higher speeds than the 5 knots shown in Fig. 19. The impact of the higher speed on scale effect is not known.

The scale effect that is inferred from Fig. 19 data would affect the prediction of oil loss from the MDT design. All of the DHT tests were conducted under conditions of zero current and zero ship velocity. Another kind of scale effect involving the passage of oil and water through relatively small apertures internal to the model could very well be present on the DHT design, however, there were no tests conducted to determine this effect.

Tests were also conducted at DTMB that showed differences in oil loss between the two MDT models under combined current and oscillation conditions where the oscillation represented a vertical ship motion caused by sea state. The data will not be shown here, however, there were discrepancies (similar to the Fig. 19 data) in the oil lost between the 1/15 and 1/30 models that could not be explained away by considering the relative oil tank capacities of the 1/15 and 1/30 scale model. See reference 7 for the data.

The model tests conducted at Tsukuba and at DTMB define the existing state-of-the-art practice regarding such model tests. The purpose in discussing the scale effects is to show the deficiencies with regard to the existing practice end, although a set of recommendations for improving the existing practice is presented later in this report, it should be realized that these test data are the best data that

are available for evaluating the oil spill characteristics of the proposed concepts.

SIGNIFICANT MODEL TEST RESULTS

TSUKUBA TESTS OCT-NOV 1991

1. MDT oil loss due to 3 knots current only about 1% of damaged tank after 2 hours operation.
2. MDT oil loss due to current and combined current and oscillation insensitive to orientation of damaged hole.
3. Initial rate of oil loss and total MDT oil loss very high at 7 knots current suggests rupture test, initial exchange loss.
4. Oil loss due to oscillation only (sea state induced) is very small.
5. Oscillation significantly magnifies oil loss due to current. MDT oil loss due to 3 knots current and oscillation (BF8 condition) is about 2% of damaged tank after 2 hours operation.
6. DHT - rupture test shows high loss of oil. Test scenario with double hull space flooded is criticized. IMO specifies "U" tanks instead of "J" tanks for DTMB tests and a test scenario with air in the double hull space. The "J" tank captures only 14% of oil exiting the cargo tank.

DTMB TESTS DEC 1991-FEB 1992

1. MDT test with 1/15 and 1/30 scale model suggest possible scale effect.
2. Repeat tests agree with Tsukuba data with respect to oil loss due to current.
3. MDT rupture and stop tests define initial exchange loss. Initial speed and hole width variation.
4. DHT rupture tests successfully completed with "U" tanks and air in double hull space. "U" tank much more effective than "J" tank in terms of capturing leaking cargo oil. The "U" tank captures 76% of oil exiting the cargo tank.
5. MDT rupture and continue tests conducted, 5.7% oil loss after 2 hours operation.
6. MDT partial load rupture and stop test. Half full cargo tank has only 1/6 the oil loss of a full tank.

TSUKUBA TESTS JAN 1992

1. MDT rupture and stop tests in general agreement with DTMB tests.

2. MDT rupture and continue test shows 8% oil loss after 2 hours. Large oil loss relative to DTMB probably due to difference in rupturing mechanism and rupture hole geometry.

COMPLETENESS OF TESTING

An examination of the model test data shows that the following tests which could be considered important were not performed.

DOUBLE HULL MODEL

- Rupture and stop tests
- Rupture and continue tests
- Scale effect
- Oil loss due to current, sea state

All double hull testing was at zero speed and there was only one double hull model, so scale effect tests where not done. There were only two rupture tests, both at zero speed. At the time of testing it was felt that due to the large water layer in the double bottom, which is usually present subsequent to rupture, the forward speed effects might be less than on a mid deck design. It is now realized that the large water layer is only present for "U" tank designs, and is generally not present for "J" tank designs. The forward speed might in fact be a significant influence with regard to instantaneous exchange loss in that it could affect the ability of the double hull spaces to capture oil exiting the cargo tank.

MID-DECK MODEL

- Scale effect tests were only performed for current and sea state loss. They were not performed for any of the rupture tests.

RECOMMENDATIONS

It is recommended that an evaluation/prediction capability be developed that enables a more accurate assessment of oil outflow due to grounding. This capability would not require a model test for each design that is to be evaluated. Such evaluation capability is a key element to a probabilistic approach that evaluates the total oil pollution potential of a design and includes other factors such as fire collision structural failure and total ship loss. Development of the plan for the oil outflow

assessment due to grounding is shown in Fig. 20. This plan was formulated from a knowledge concerning the shortcomings of the existing model testing procedure and from observations of the oil loss phenomena that occurred during the model testing. Major elements of this plan are:

Basic Hydrodynamic Analysis: The task will start with a basic phenomenalogical research to establish a law of similitude for the phenomenon. This will include dimensional analysis of all the important parameters that could influence oil loss due to grounding and due to the subsequent environmental factors, tide, sea state, and current. Based on our present understanding of oil loss, the following flow phenomena would be examined:

- Stratified oil-water flow in a tank and through restricted openings. This work would examine the flow through and around the structural members in the tank such as the bulkheads in the mid-deck designs and the longitudinal bulkheads and stiffeners that are present in the double hull space of the Double Hull Tanker designs. It would also examine the oil-water wave system formed at the time of rupture.
- Stratified oil-water flow disturbance caused by external water flow: This work would examine the mechanism by which the water flow outside the rupture hole induces flow oscillations and oil water waves inside the tank. The amount of oil lost through the process of clipping off the bottom of the oil wave troughs would be examined.
- Mixing at the oil-water interface and formation of oil droplets: This work would examine the interaction of oil and water and estimate the oil loss through the process of oil droplet formation.

Structural Dynamic Analysis: The oil loss is clearly dependent on the size of the damage hole. In addition, for the instantaneous exchange loss it is important to know the ship deceleration and the rate of damage hole formation. Other structural details that need to be addressed are the maximum size and number of limber holes and through holes that can be readily accommodated by a structural member, such as in the double hull space, without sacrificing structural strength.

Prediction of Instantaneous Exchange Loss: The above Hydrodynamic and Structural Analysis will be synthesized into a computer code for the prediction of the instantaneous exchange loss.

Oil Loss Due to Sea State, Tide, and Current: The effect of cargo tank motions on oil loss and the prediction of ship motions for a grounded ship will be needed for assessing the effect of sea state. Tide drop effects are treated hydrostatically, and the effect of current will have been previously established under the basic hydrodynamic analysis.

Verification Hydrodynamic Model Tests: The above developed oil loss algorithms will be verified and improved through model testing. New types of model tests specially designed for the problem may be needed to verify some of the stratified oil water flow computer codes. It is also anticipated that since full scale oil loss testing is impractical, several model tests will be required to ensure that the scale effects is understood. Tests with different model size are envisioned for:

- oil loss due to current
- instantaneous exchange oil loss
- oil flow in double hull space or through MDT cargo tank bulkheads

Some model tests, designed to explore the nature of oil water flow in double hull spaces are envisioned to be conducted with very large models. This can be accomplished at zero forward speed in an outdoor test facility. Other model tests are envisioned that are conducted to further define the instantaneous exchange loss and the effect of current and sea state. Models that represent just the cargo tank and model s that represent the entire ship would be considered.

The final product of the above effort would be an evaluation capability for oil loss due to grounding. Individual tankage and structural geometries could then be evaluated (without model tests) to determine their resistance to accidental oil pollution.

SUMMARY

These oil spill model tests, both at Tsukuba and at DTMB, provide technical guidance for the evaluation of oil spill characteristics of the Mid-Deck Concept and the Double Hull Concept. The tests clearly showed that the Mid-Deck Tanker Concept will have an initial exchange loss and that this loss is heavily dependent on the ship's forward speed prior to the grounding. For the Double Hull Tanker Concept, the tests showed that the space between the inner and outer hull can capture oil that may be spilled from the main cargo tank and that the amount of oil captured will be greatly dependent on the

internal subdivision of these spaces, "J" tank or "U" tank arrangement. The following is a synopsis of the test results:

INSTANTANEOUS EXCHANGE LOSS

MDT Design

This oil loss was shown to be very much dependent upon the initial speed. At 10 knots, the average loss per tank was 1.2% of the lower oil cargo tank volume that was ruptured. At 15 knots initial speed, the loss is estimated to be 5 times as much.

DHT Design

All tests were performed at zero initial speed. The "U" tanks retained 76% of the oil that exited the cargo oil tank, the "J" tanks retained only 14% of the oil. With the "U" tanks, the loss was 6.2% of the volume of the damaged cargo oil tank. This is with no blockage of rupture hole. With the "J" tanks, the loss was much greater, however, the test was a combined tide drop and rupture test.

OIL LOSS DUE TO TIDE DROP

MDT Design

There is no loss at the specified 6 meter tide drop.

DHT Design

There is no loss with "U" tanks at the specified 6 m tide drop. With "J" tanks there would be a significant loss.

OIL LOSS DUE TO CURRENT

MDT Design

The oil loss is 1% of damaged tank volume at 3 knots current after 2 hours exposure.

DHT Design

No tests done.

OIL LOSS DUE TO OSCILLATION

MDT Design

There is no loss with 600 mm design water layer, BF8 sea state simulation.

DHT Design

No tests done.

OIL LOSS DUE TO CURRENT AND OSCILLATION

MDT Design

The oil loss is 2% of damaged tank volume with 600 mm water layer, 3 knot current, and oscillation simulating BF8 condition for 2 hour exposure. This applies only to the tank in the location that was tested.

DHT Design

No tests done.

RUPTURE AND CONTINUE AT SPEED OIL LOSS

MDT Design

The oil loss after 2 hours operation at 10 knots is 5.7% of damaged tank from DTMB tests, approximately 8% from Tsukuba tests.

DHT Design

There were no tests done because this scenario is highly unlikely for DHT. A rupture of the inner hull would be a severe accident that would be noticed and the ship would stop. A low energy outer hull only rupture will have no oil loss.

It is believed that there are model scale effects that introduce an element of uncertainty with regard to oil loss predictions based on results from model testing. Due to geometry differences between the 1/15 and 1/30 MDT models, it is not possible to quantify these effects using the experimental results reported here. The resolution of these scale effects is very important to the accurate prediction of oil loss.

OVERALL OIL LOSS ASSESSMENT

An overall oil loss assessment is beyond the scope of this report. Such an assessment, even for the oil loss due to grounding, will be dependent on the probable occurrence of various damage scenarios and the extent of damage incurred by Mid-Deck and Double Hull tankers. It is also important to realize that the oil losses listed in the Summary are, in general, not linearly additive. For example, the magnitude of the initial instantaneous exchange loss will affect subsequent oil loss due to environmental effects. Thus, an overall oil loss assessment will have to take into account the interrelationship between the various oil losses.

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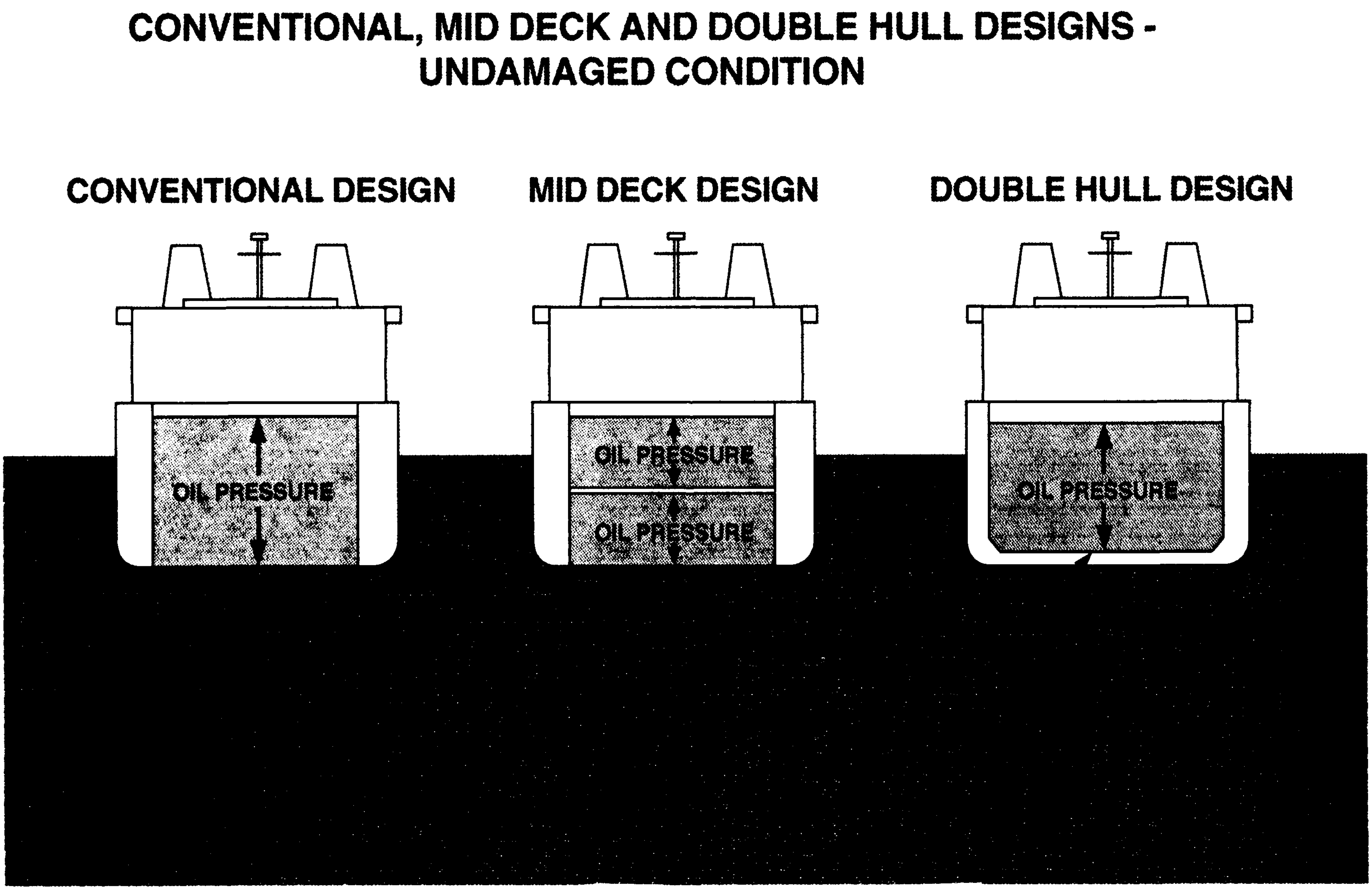


Fig. 1. Conventional, Mid-deck and Double Hull Designs - Undamaged Condition.

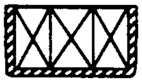
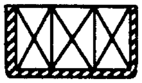
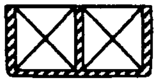
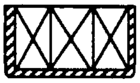
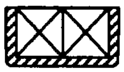
SHIP CODE	ARRANGEMENT	LENGTH DEPTH	BEAM DRAFT	HEIGHT OF DOUBLE BOTTOM	CARGO TANK VOLUME	DWT (TONS)
MITSUBISHI 02-DH-280		318.00 31.50	58.00 21.50	3.00	344,000	280,000
HOWALDTSW. 04-DH-280		318.00 30.20	57.00 20.90	4.00	331,000	280,000
MARINEX 07-DH-280		324.60 29.50	54.10 20.70	2.13	335,899	282,000
ODENSE 08-DH-280		327.00 30.40	56.40 21.80	3.20	340,800	293,000
IHI 01-DH-150		263.30 24.70	44.50 16.90	2.97	167,100	142,000
FINCANTIERI 09-DH-150		264.0 23.8	45.4 17.1	2.60	166,400	150,000
ASTILLEROS 16-DH-150		253.00 24.20	45.00 17.30	3.00	166,297	150,000
MITSUI 03-DH-90		232.80 20.60	42.00 14.00	2.49	118,000	98,000
BURM&WAIN 19-DH-90		243.0 19.00	32.20 14.50	2.15	91,487	80,723
TSUNEISHI 06-DH-40		172.00 18.20	31.00 11.12	2.07	50,500	40,108
BURM&WAIN 10-DH-40		172.80 21.60	32.24 15.50	2.15	60,223	59,189
ASTILLEROS 12-DH-40		169.50 16.60	31.00 11.10	2.07	48,300	40,115

Fig 2A. IMO Selected Double Hull Designs for Total Oil Outflow Evaluation.

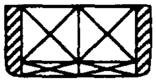
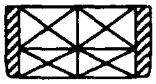
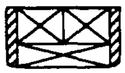
SHIP CODE	ARRANGEMENT	LENGTH DEPTH	BEAM DRAFT	HEIGHT OF MID DECK	CARGO TANK VOLUME	DWT (TONS)
CHANT. ATLANT. 05-MD-280		318.0 31.1	57.0 20.7	6.00	331,580	280,000
MITSUBISHI 11-MD-280		318.0 32.3	58.0 21.5	14.30	344,000	280,000
FINCANTIERI 14-DH-150		264.00 23.80	45.00 17.10	8.80	165,800	150,000
IHI 13-DH-150		263.3 25.6	44.5 16.9	10.00	167,970	142,000
MITSUI 15-MD-90		232.8 21.35	42.0 14.0	7.88	118,000	98,000
TSUNEISHI 17-MD-40		172.0 19.0	31.0 11.1	6.00	50,570	40,000

Fig 2B. IMO Selected Mid-Deck Designs for Total Oil Outflow Evaluation.

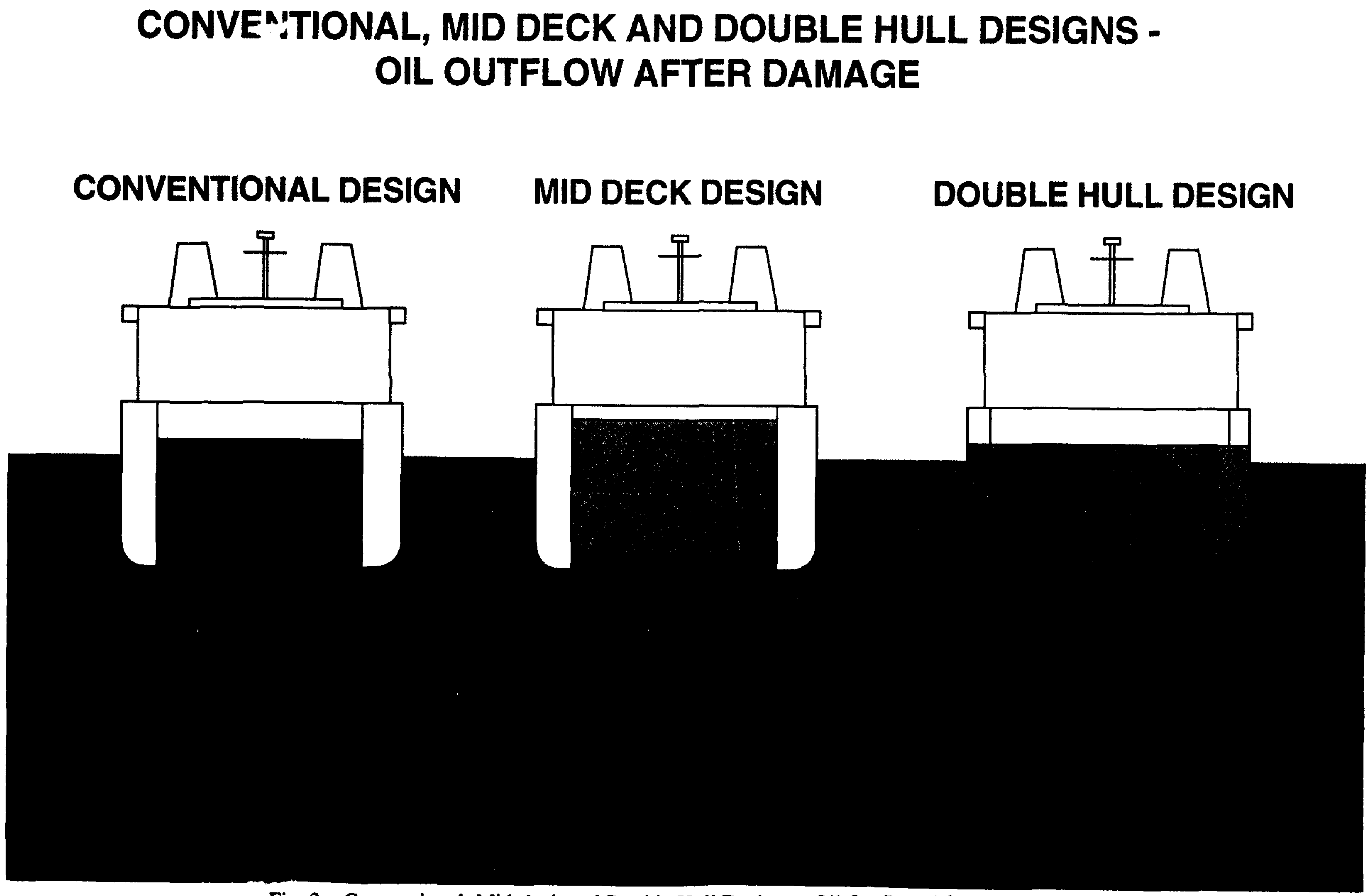


Fig. 3. Conventional, Mid-deck and Double Hull Designs - Oil Outflow After Damage.

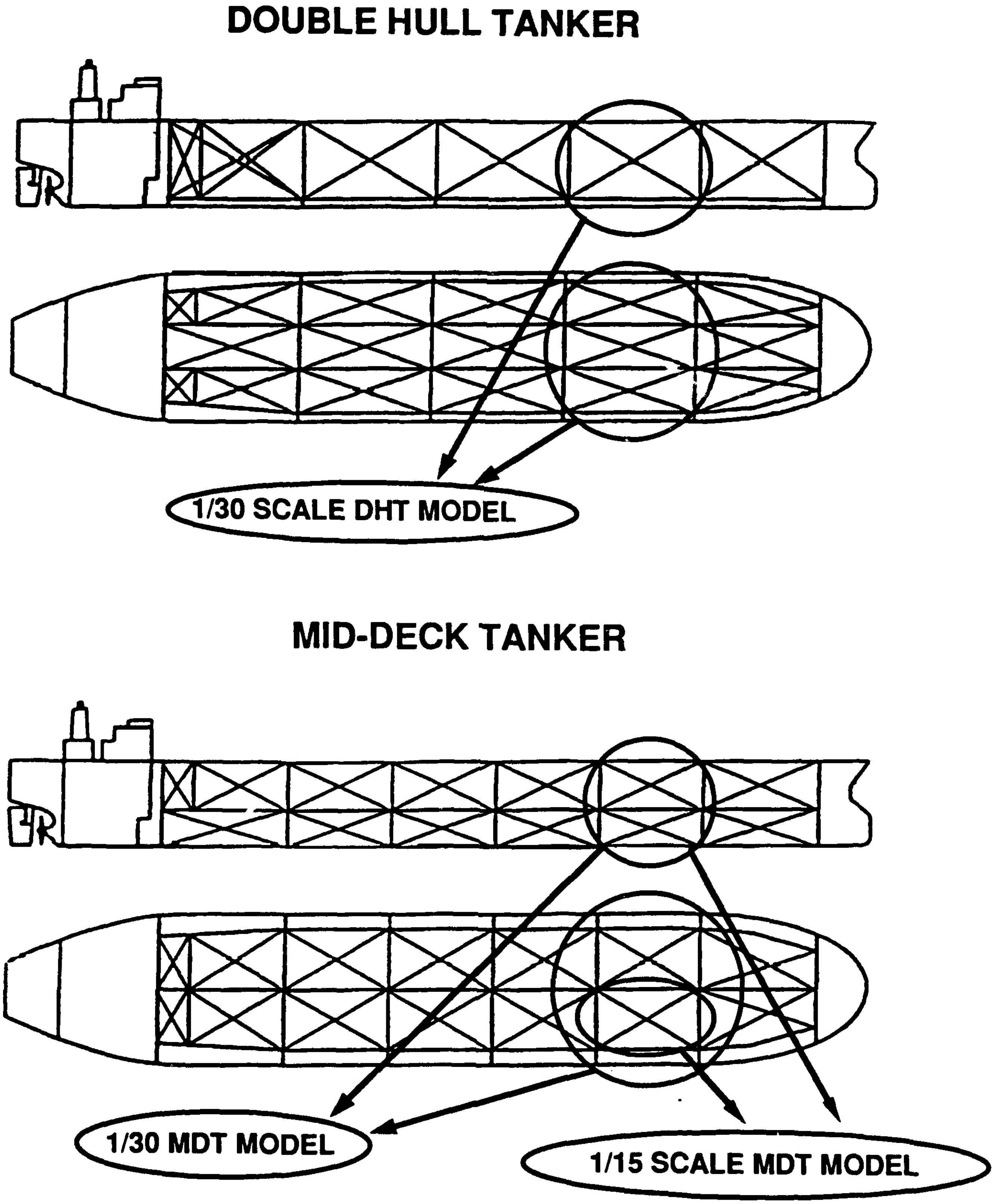


Fig. 4. Oil Tankage Arrangements Represented by the Hydrodynamic Models.

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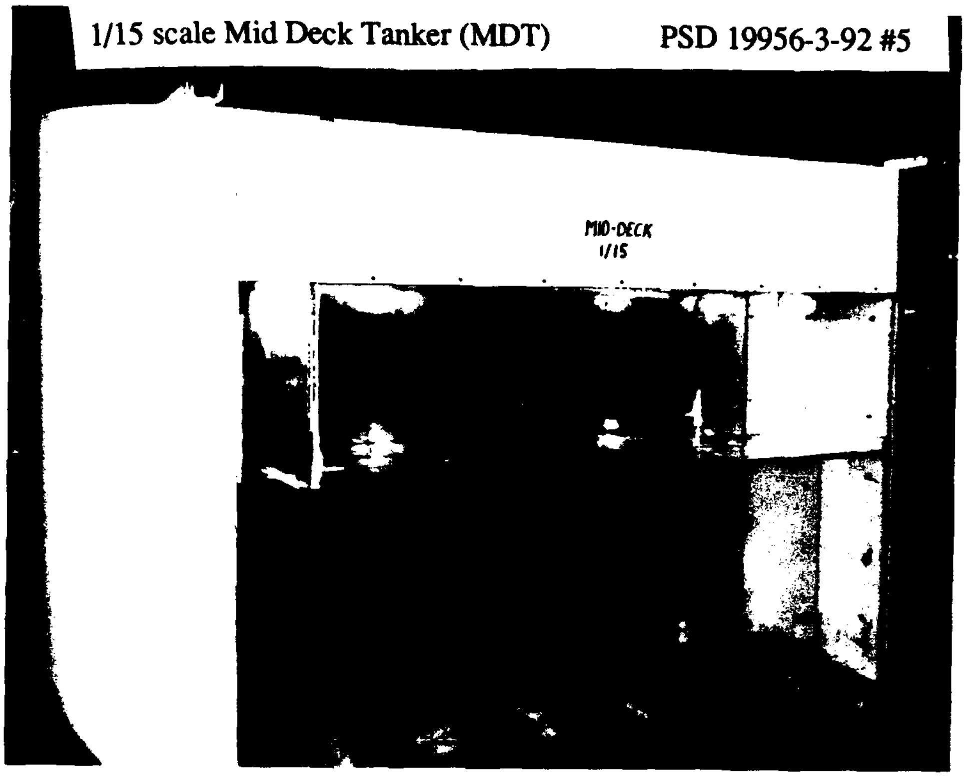


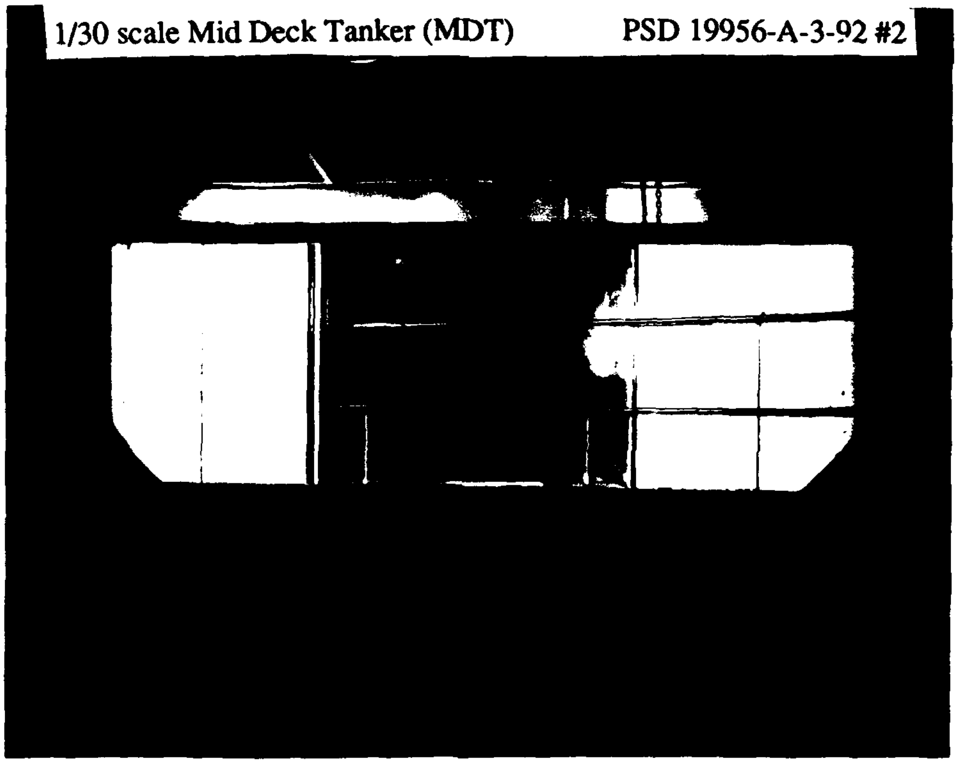


Fig. 5. Photographs showing the two 1/15 and 1/30 scale MDT models tested.

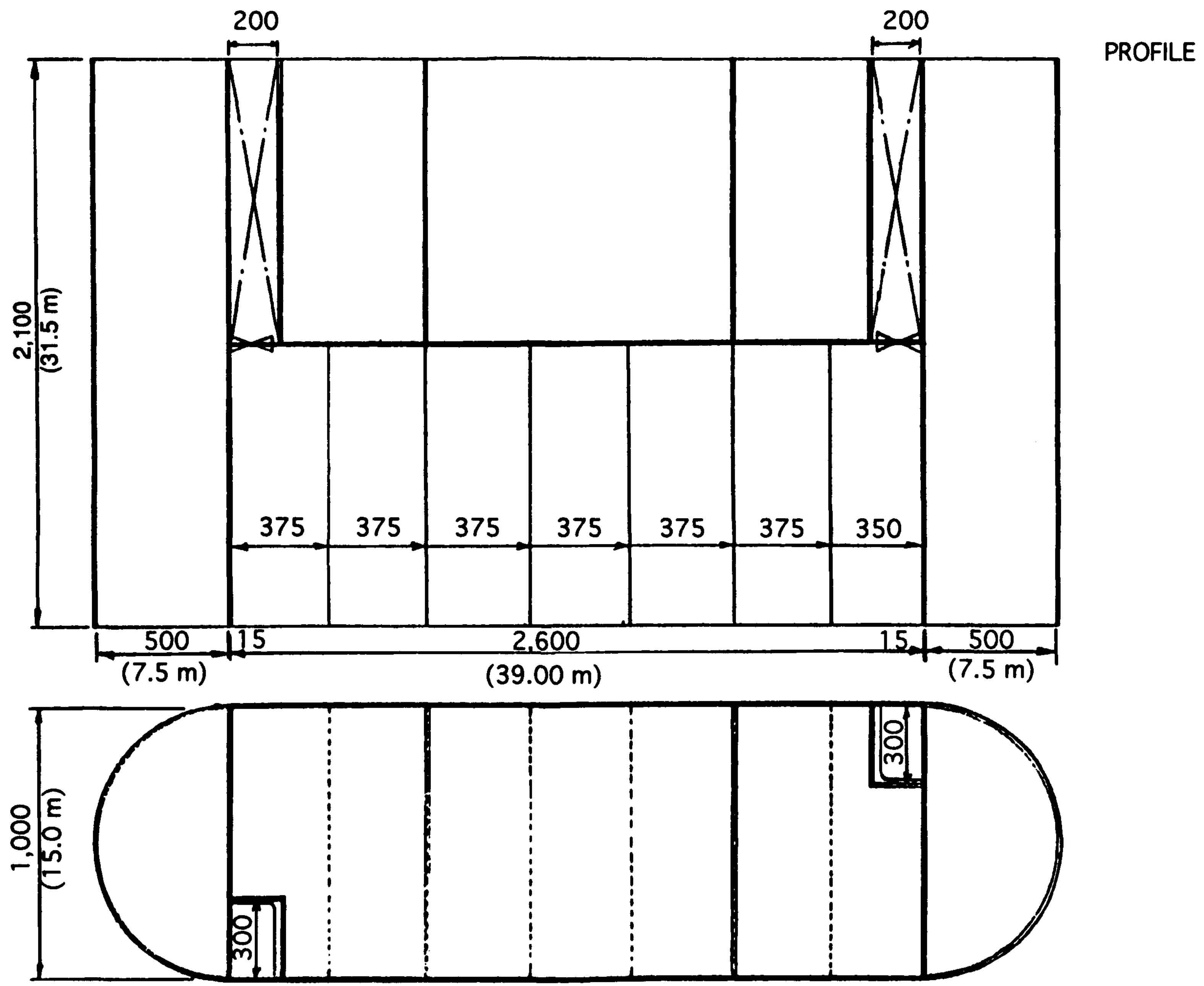


Fig. 6. 1/15 MDT Model Drawing.

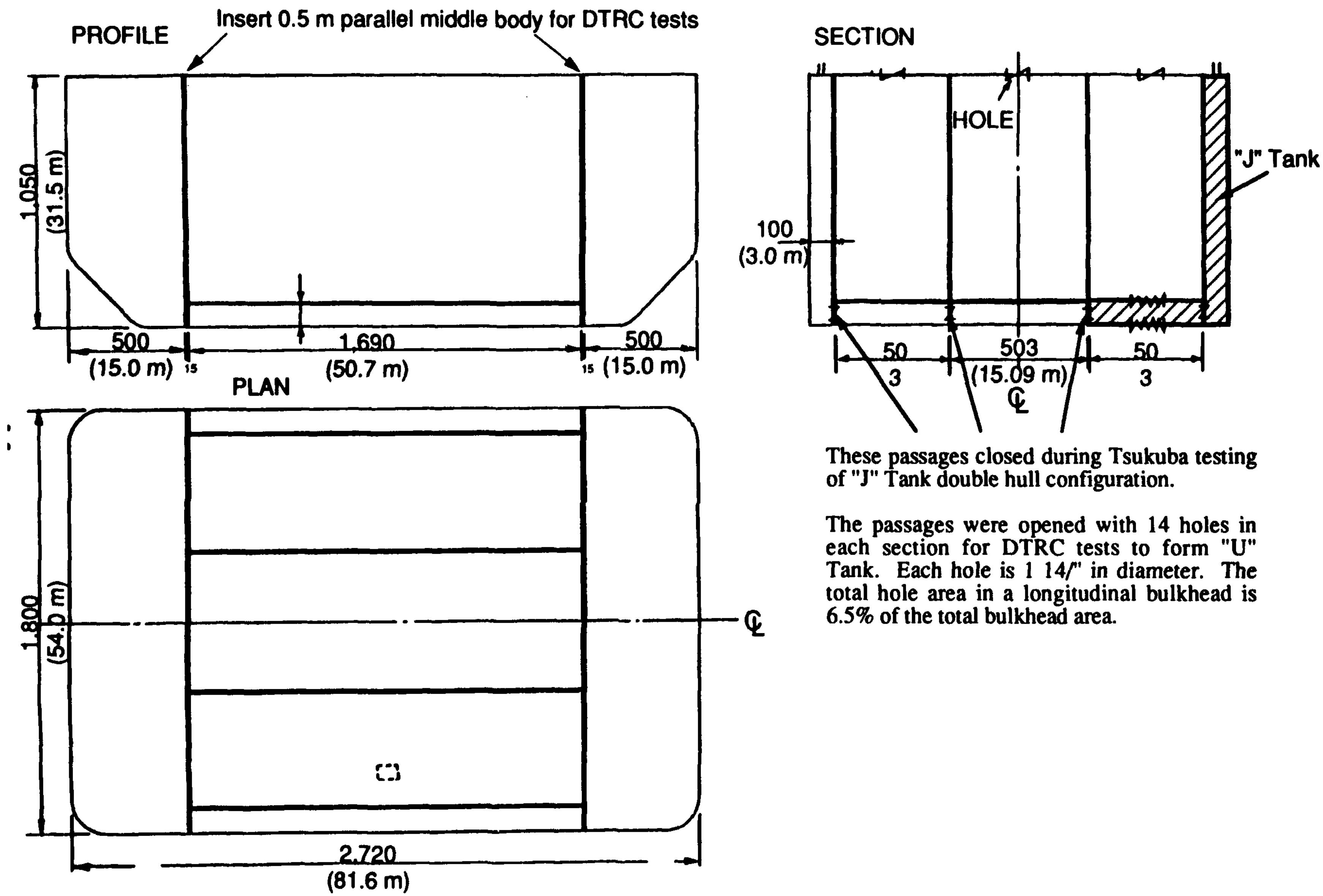


Fig. 7. 1/30 Double-Hull Tanker Model Drawing.

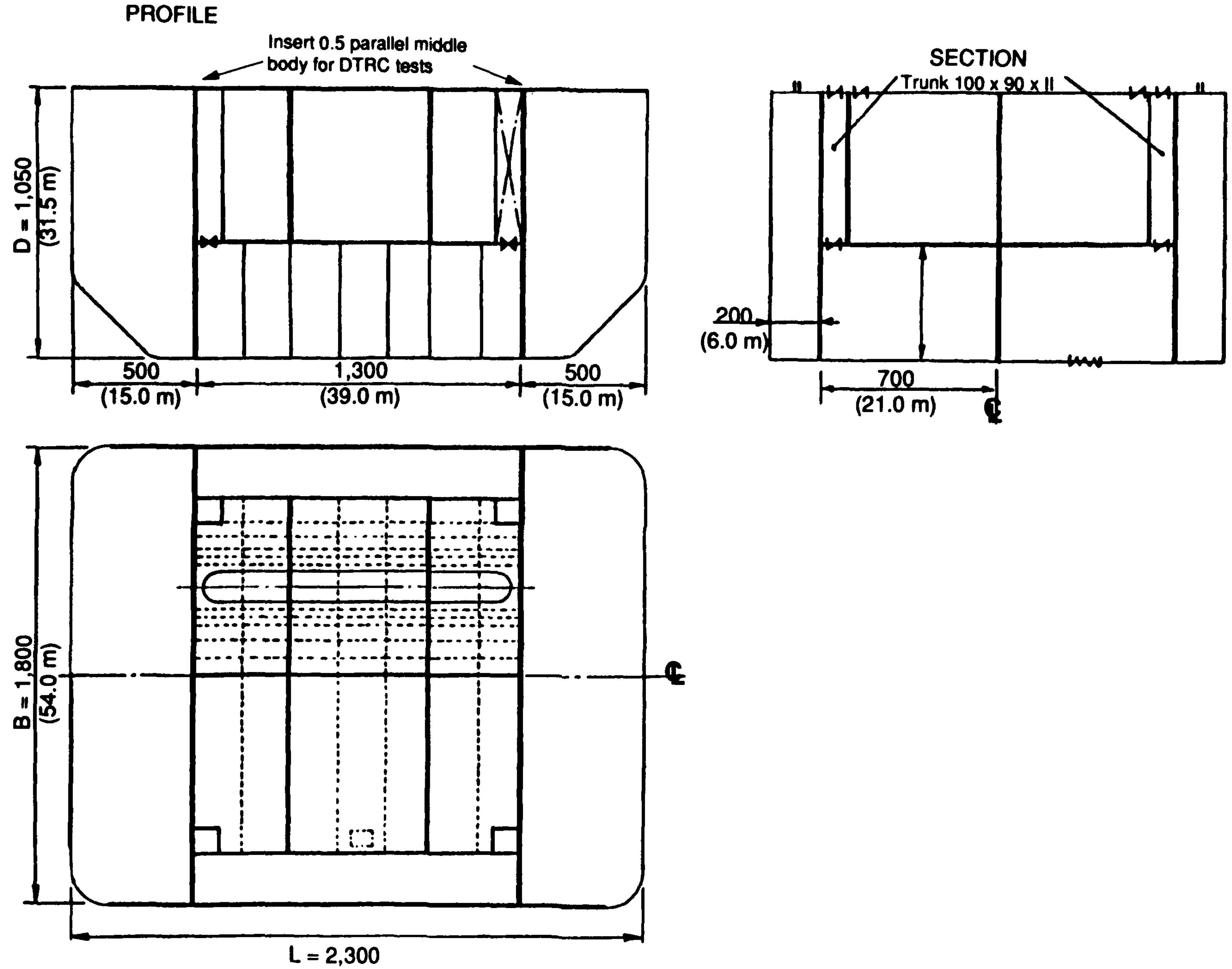


Fig. 8. 1/30 MDT Model Drawing.

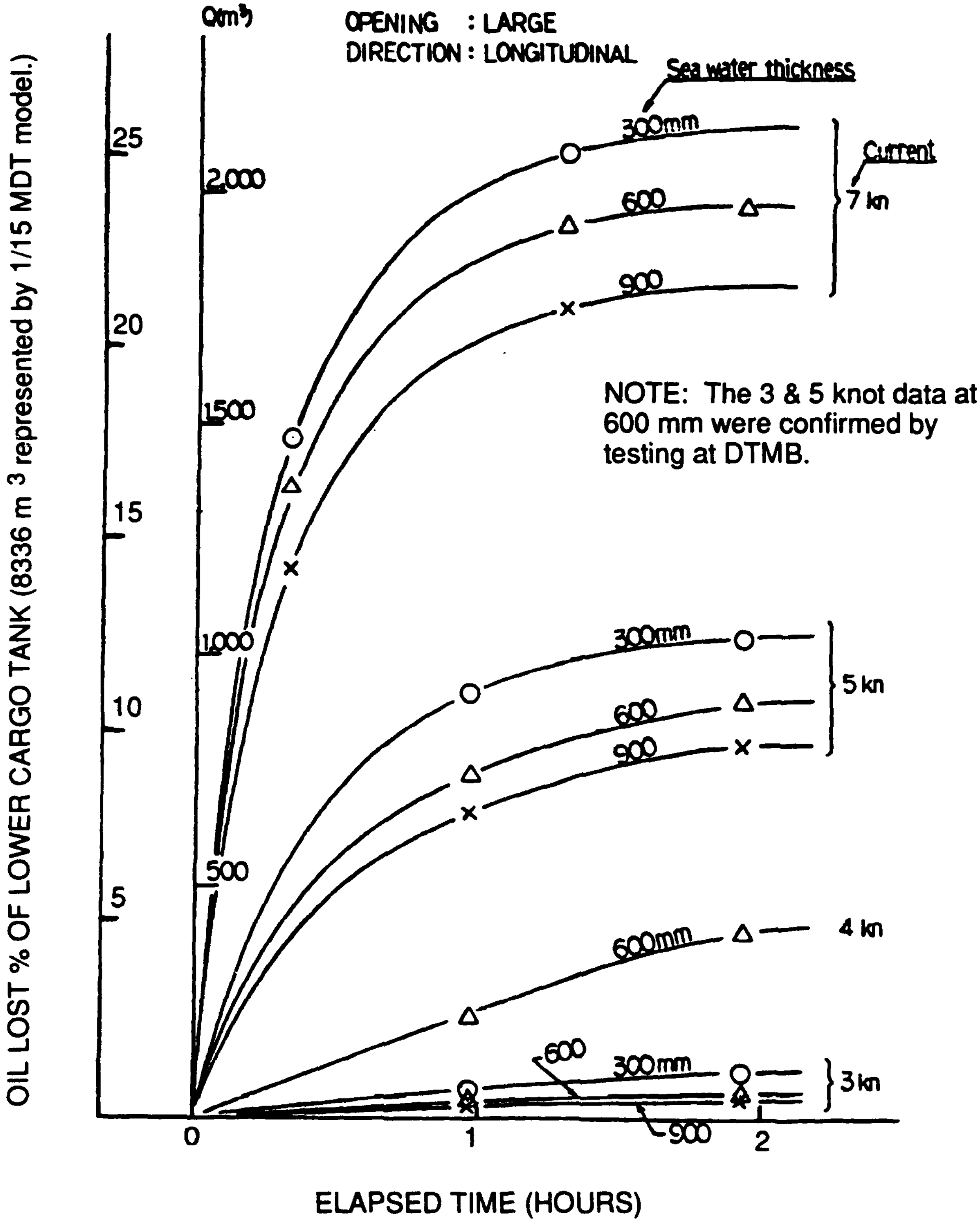


Fig. 9. Effect of Current on Oil Loss, 1/15 Scale MDT Tsukuba Data.

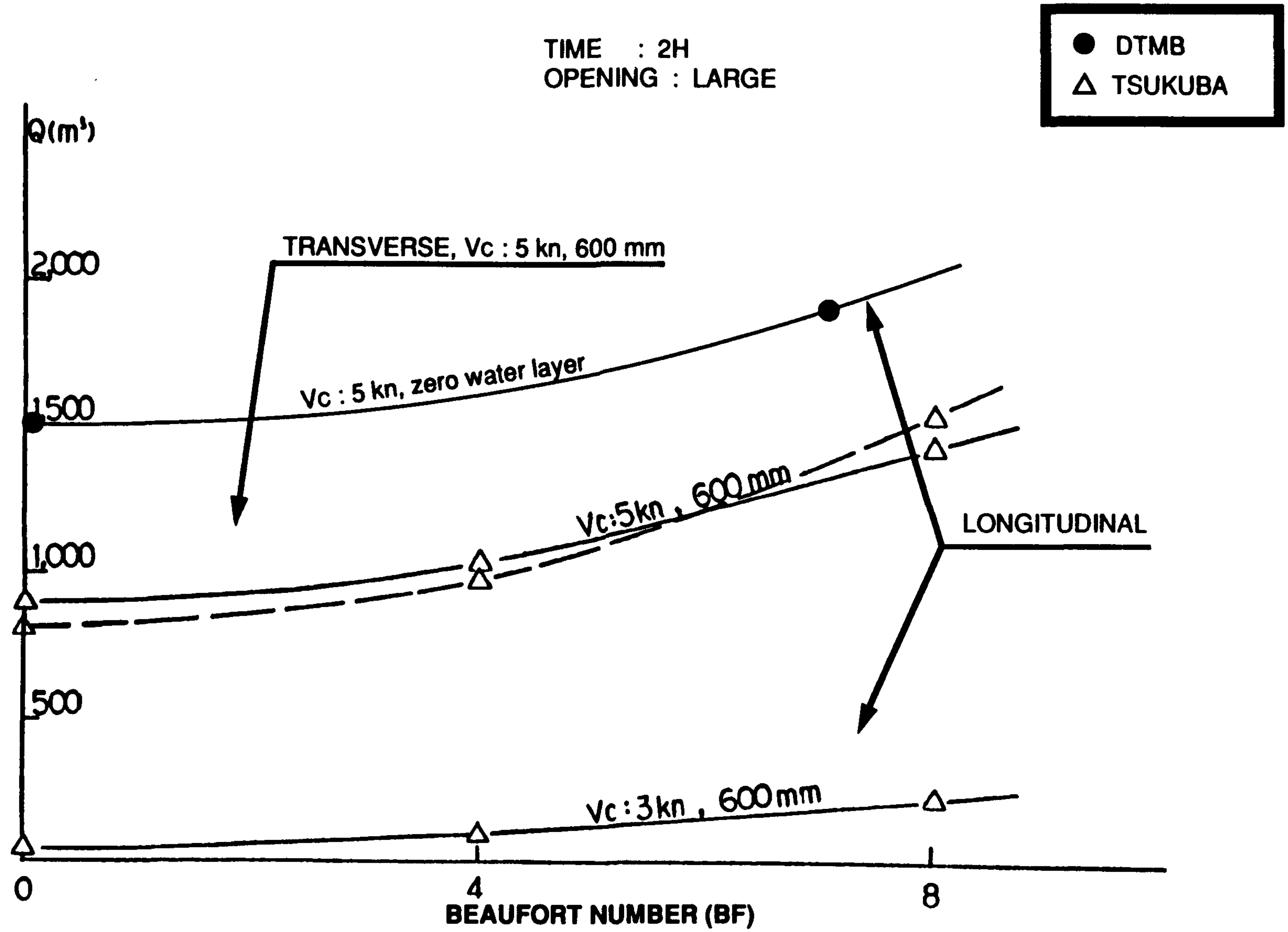


Fig. 10. Effect of Sea Condition and Damage Hole Orientation, Mid-Deck Tanker.

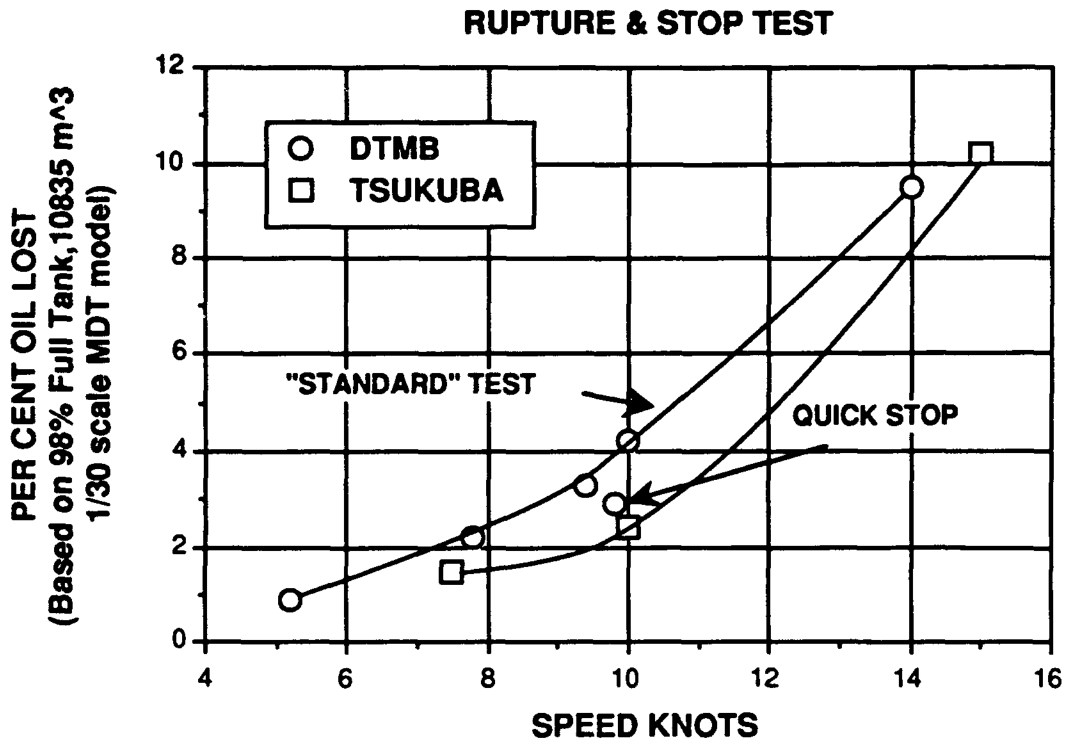


Fig. 11. Initial Exchange Oil Loss, (one cargo oil tank) Rupture and Stop Tests 1/30 Scale MDT Model.

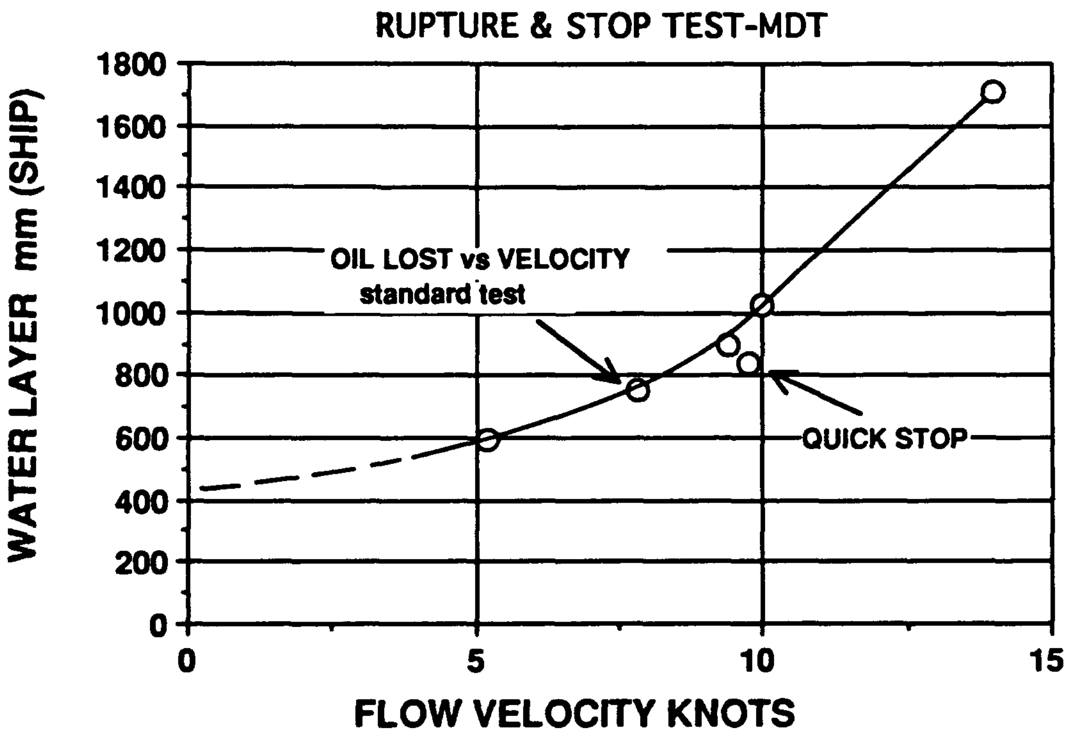


Fig. 12. Water Layer Formed Subsequent to Grounding - Rupture and Stop Tests 1/30 Scale MDT Model.

Condition: Initial Speed = 10.0 knots
Rupture Width = 3.75 m

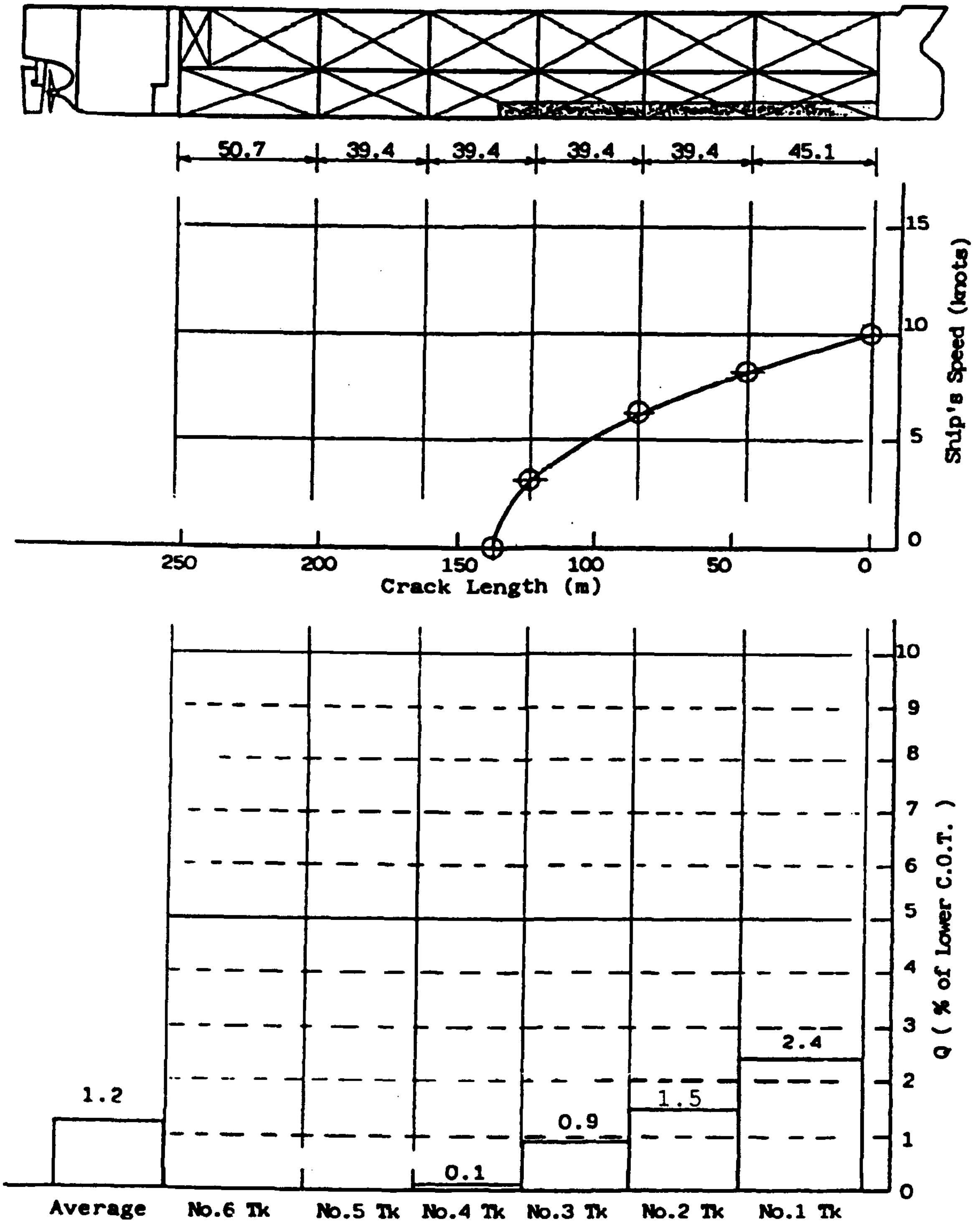


Fig. 13. Initial Exchange Oil Loss Due to the Rupturing of 4 Cargo Oil Tanks 10 Knots Initial Speed - MDT Design.

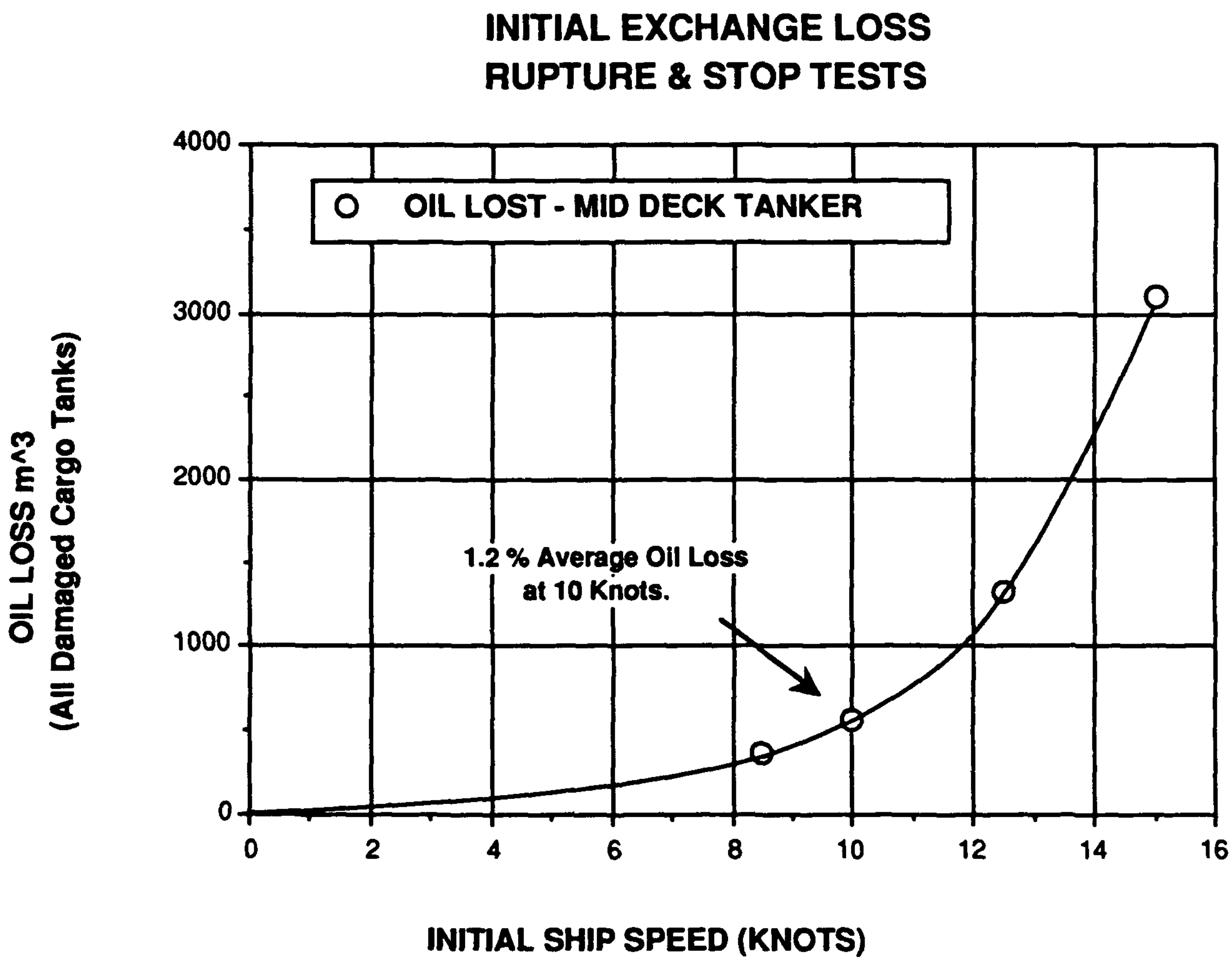


Fig. 14. The Sensitivity of Total Initial Exchange Oil Loss (all tanks) to Initial Speed - MDT Design.

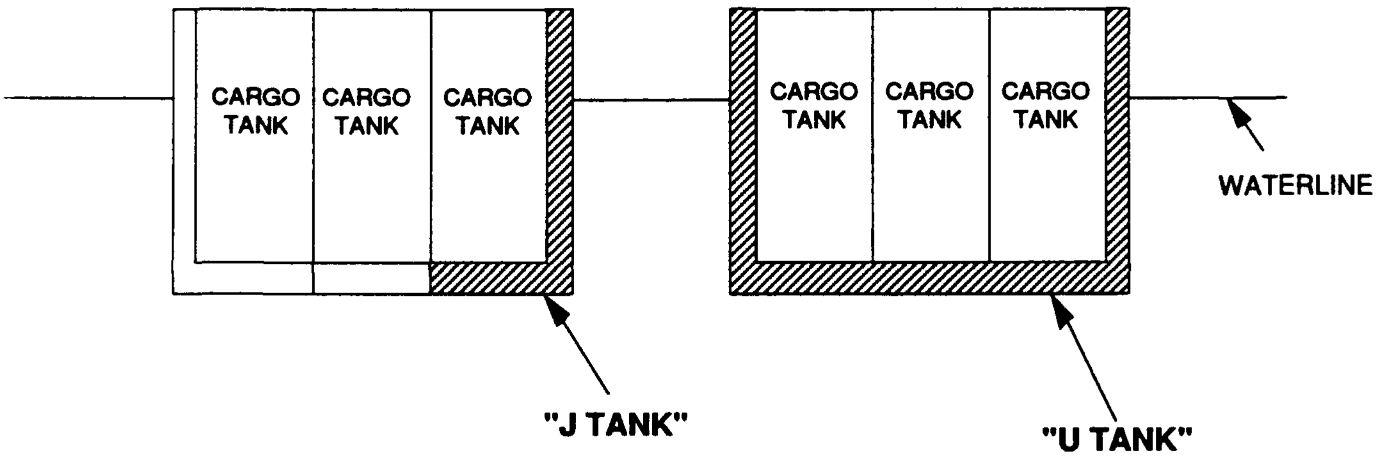


Fig. 15. Comparison of "U" Tank and "J" Tank Double Hull Configurations.

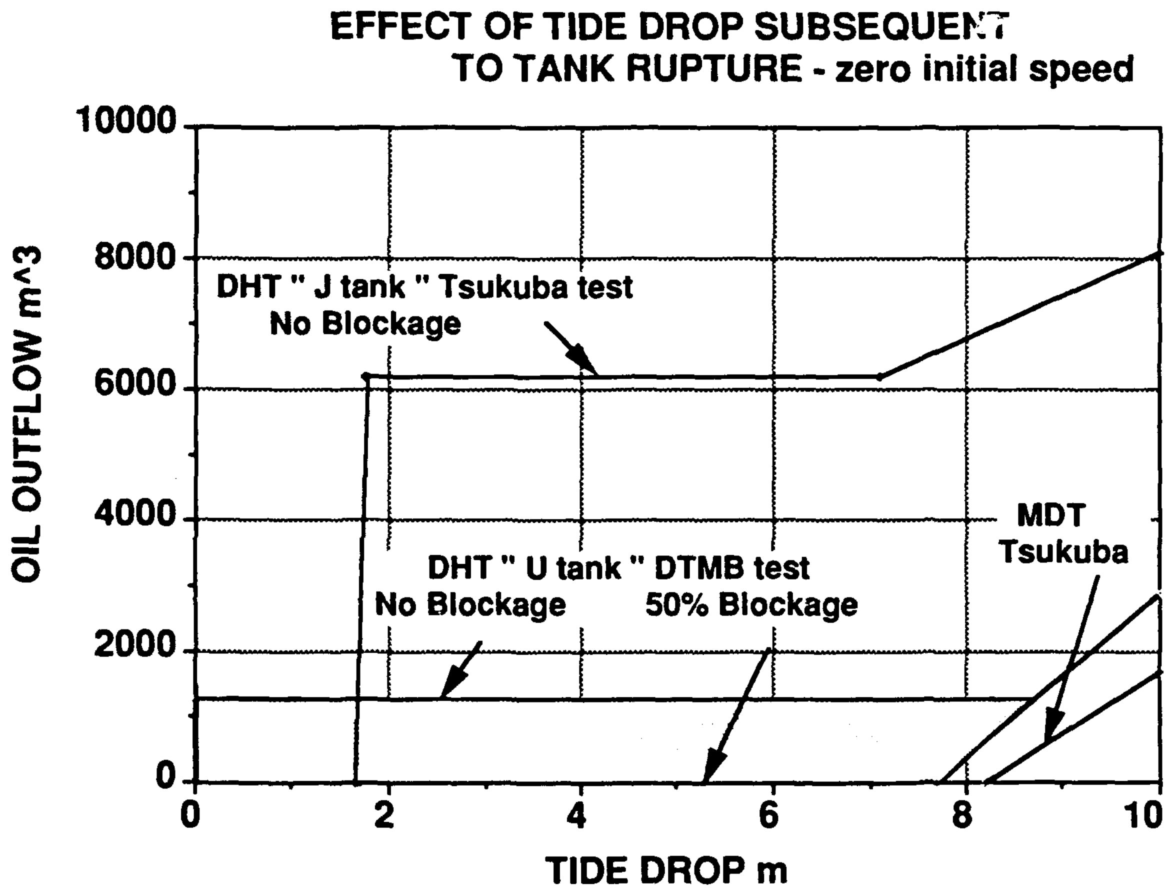
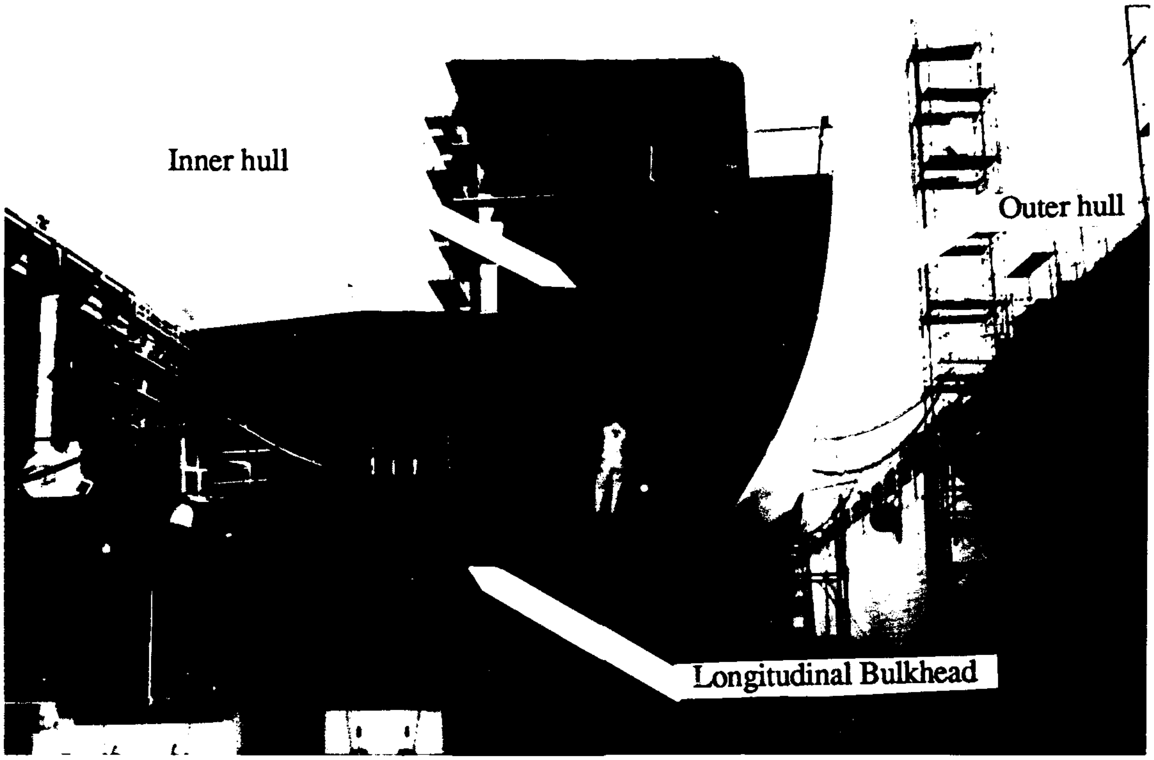
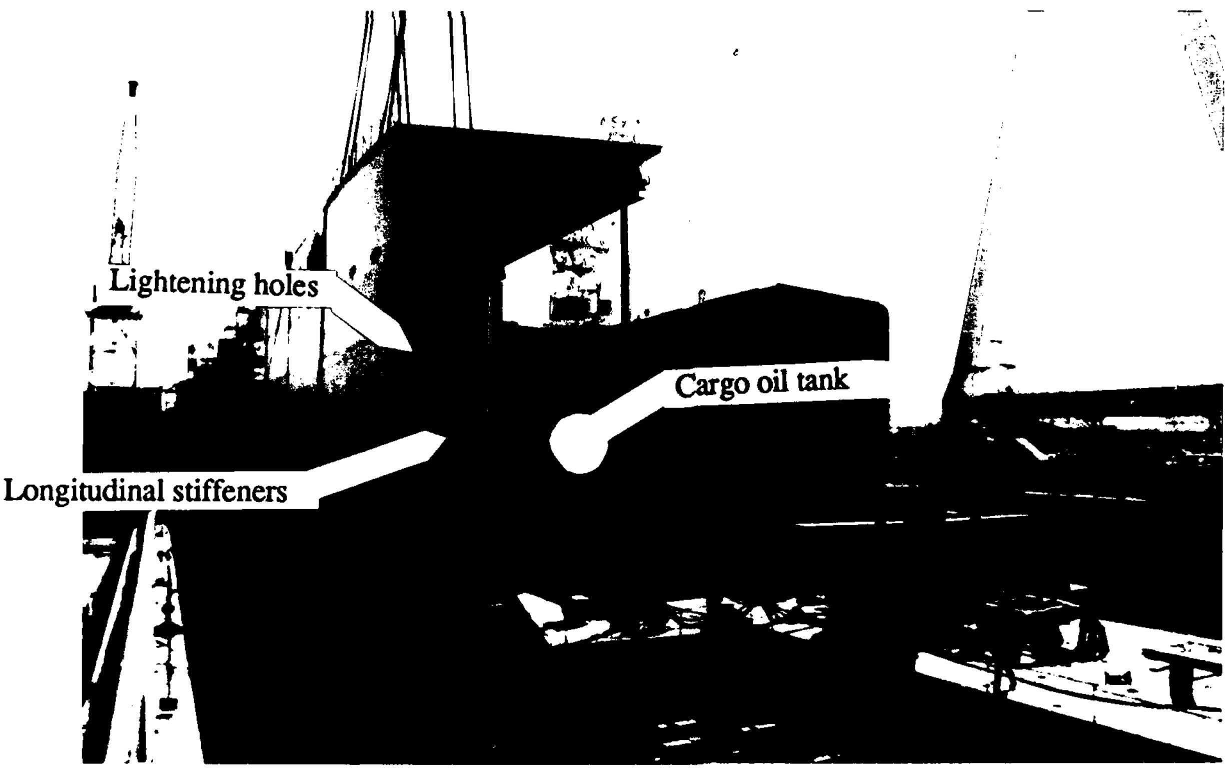


Fig. 16. Effect of Tide Drop Subsequent to Tank Rupture at Zero Initial Speed - Comparison of "U" and "J" Tanks.



Photograph courtesy of American Bureau of Shipping



Photograph courtesy of American Bureau of Shipping

Fig. 17. Structural Details of a Recent Construction Double Hull Ship

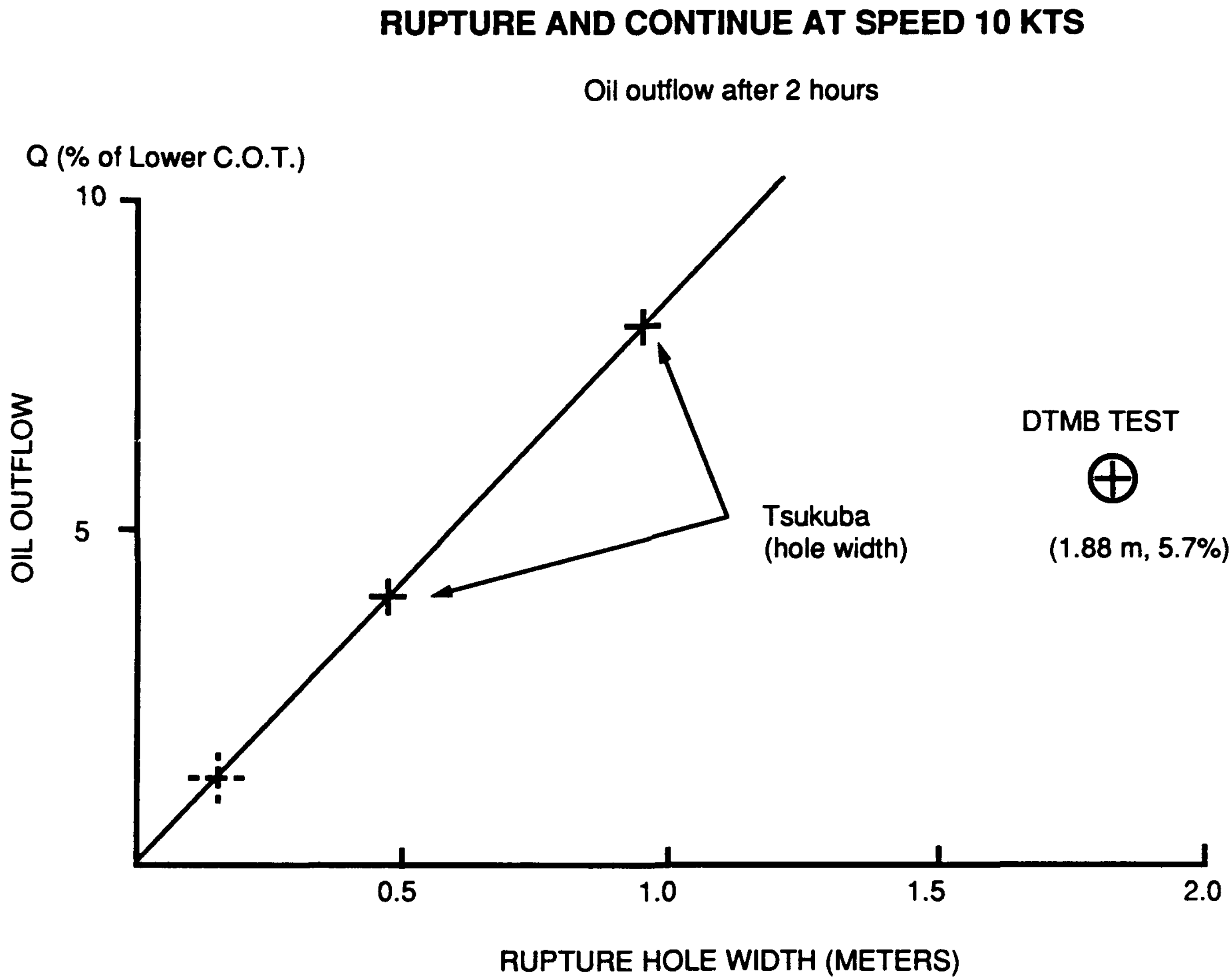


Fig. 18. Oil Loss From "Rupture and Continue at Speed" Test Scenario - 1/30 MDT Model.

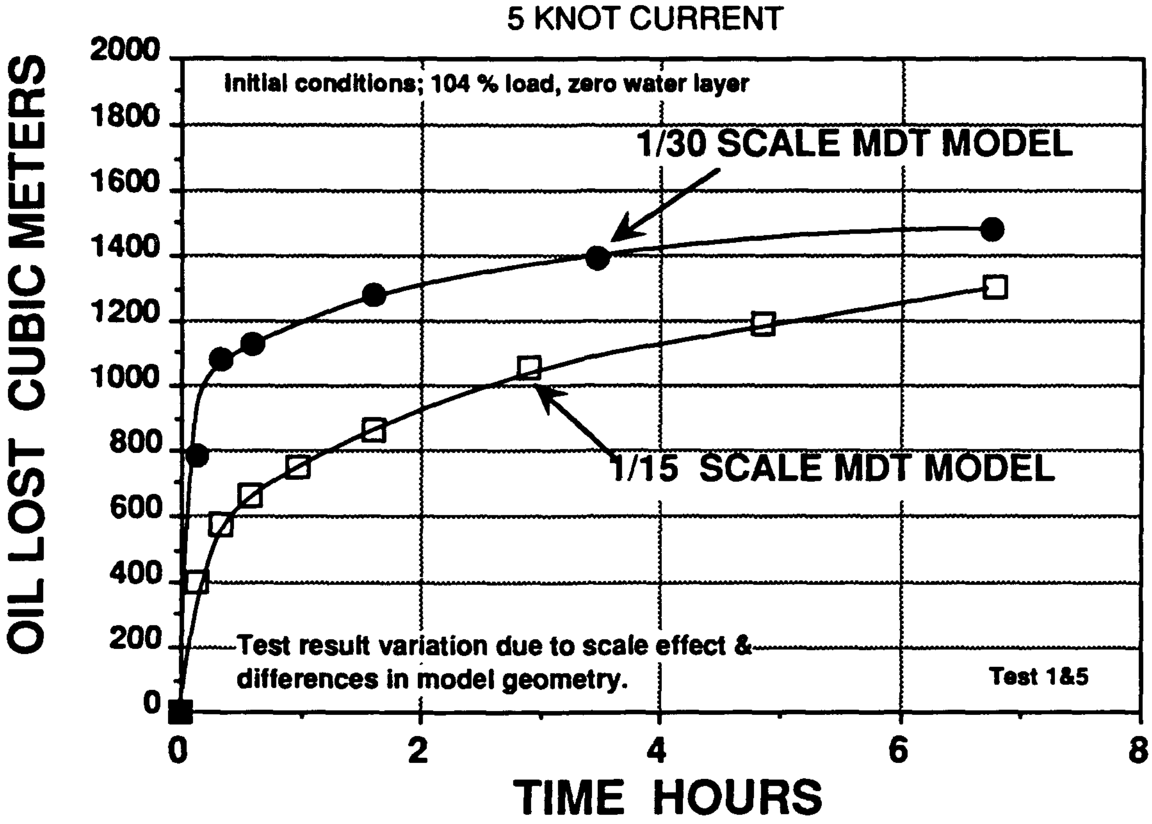
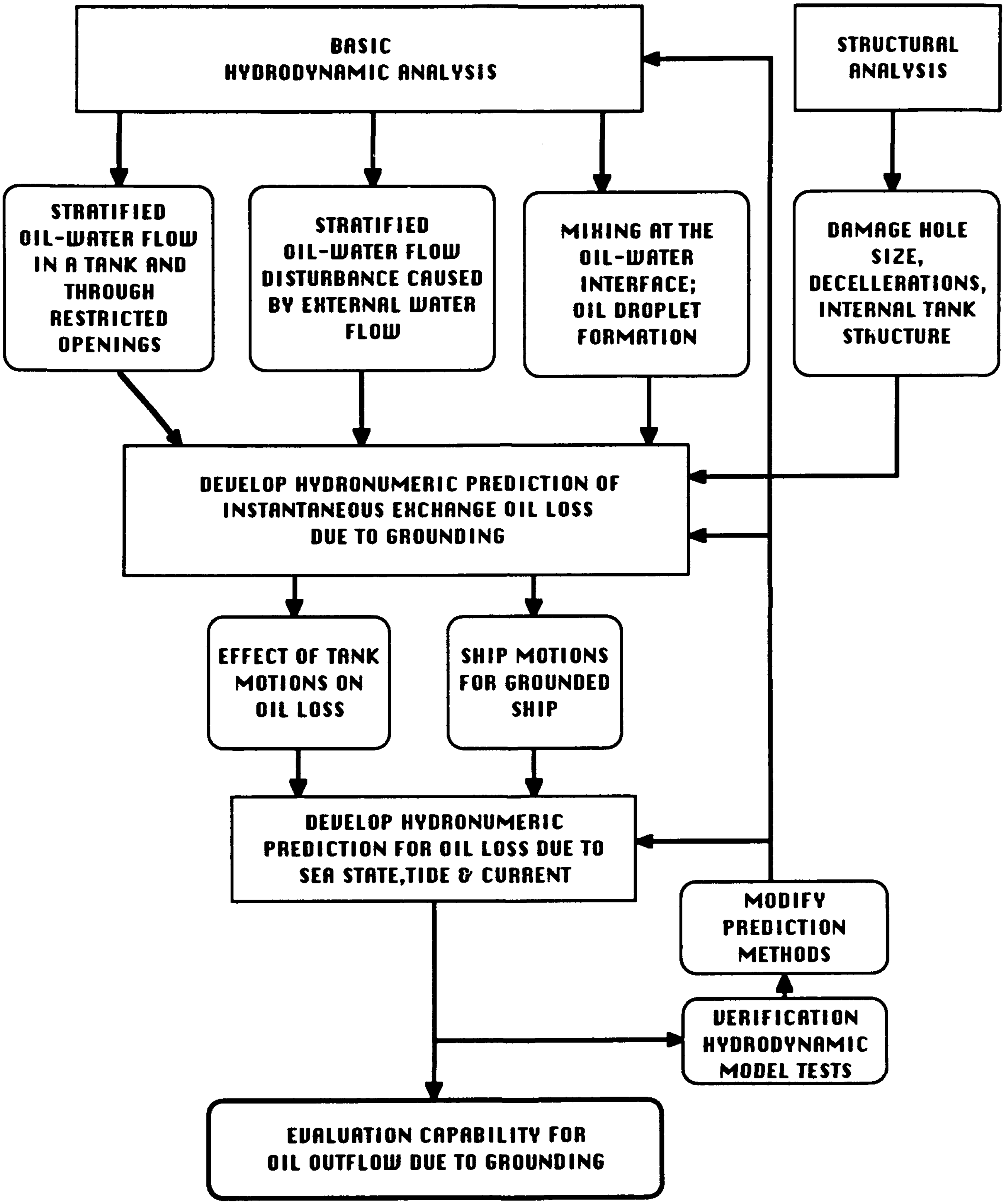


Fig. 19. Oil Loss Prediction From Two Models; 1/15 and 1/30 Scale MDT.

FIG. 20 RESEARCH AND DEVELOPMENT LEADING TO EVALUATION CAPABILITY FOR OIL OUTFLOW DUE TO GROUNDING



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APPENDIX A

MODEL TESTING CONSIDERATIONS

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It would be desirable to conduct oil loss model experiments which correctly represented all of the hydrodynamic physical phenomena that occur at ship size. This is difficult to accomplish as shown by the following discussion regarding forces on a fluid particle that are considered important to the oil loss phenomena.

STATIC PRESSURE

The static pressure in a liquid is proportional to the product of the liquid density and liquid column height. Neglecting small density differences, we have model and ship static pressures given by,

$$P_{ship} = P_{model} \cdot \lambda$$

where λ is the linear scale factor. The ratio of the oil and water static pressures is the same between ship and model

$$\left.\frac{P_{water}}{P_{oil}}\right]_{ship} = \left.\frac{P_{water}}{P_{oil}}\right]_{model}$$

The liquid static pressure is a most important factor in determining the initial exchange oil outflow and it is imperative that the ratio between the water and oil pressures be the same for ship and model.

INERTIAL FORCES - FROUDE NUMBER

The inertia forces (mass x acceleration) are properly scaled in a model test with respect to the gravitational force (mass x gravitational acceleration, g) if the ship and model Froude numbers are the same. That is,

$$Fn = \frac{V_{ship}}{\sqrt{g\,L_{ship}}} = \frac{V_{model}}{\sqrt{g\,L_{model}}}$$

and for a model with a linear scale factor λ, the model speed, Vmodel (or current velocity in our case) will be given by

$$V_{model} = V_{ship} / \sqrt{\lambda} \quad \text{(Froude scaled test)}$$

VISCOUS FORCES - REYNOLDS NUMBER

The viscous forces with respect to the inertia forces are properly scaled if the Reynold's number between ship and model constant. That is,

$$Rn = \frac{V_{ship} \cdot L_{ship}}{\nu_{ship}} = \frac{V_{model} \cdot L_{model}}{\nu_{model}}$$

Neglecting slight differences between the kinematic viscosity, ν_{ship} and ν_{model} the model speed (current velocity) for a constant Rn test will be given by

$$V_{model} = V_{ship} \cdot \lambda \qquad \text{(Reynolds scaled test)}$$

SURFACE TENSION FORCES - WEBER NUMBER

The surface tension forces with respect to dynamic pressure forces are properly scaled if the ship and model Weber numbers are the same. With the model and ship oil density the same, and the model and ship water density the same, the expression for Weber number is

$$Wn = \frac{V_{model}}{\sqrt{\frac{\sigma_{model}}{\rho_{model} L_{model}}}} = \frac{V_{ship}}{\sqrt{\frac{\sigma_{ship}}{\rho_{ship} L_{ship}}}}$$

where ρ is the density of the heavier liquid water and

σ is the surface tension

thus, the model speed will be

$$V_{model} = V_{ship} \cdot \sqrt{\lambda}$$

The oil droplet formation at the oil water interface is considered to be dependent on the dynamic pressure forces which tend to cause droplet formation and the surface tension forces which retard the droplet formation.

The following table shows the water velocity and the time duration that would be associated with a scale factor $\lambda = 30$ model if Froude number, Reynolds number and Weber number were held constant.

ITEM	SHIP QUANTITY	MODEL QUANTITY CONSTANT FROUDE NUMBER	 CONSTANT REYNOLDS NUMBER	 CONSTANT WEBER NUMBER
Cargo tank length	39 meters	1.3 meters	1.3 meters	1.3 meters
Velocity	10 knots	1.83 knots	300 knots	54.7 knots
Time	1 hour ship duration	11 minutes test duration	4 seconds test duration	22 second test duration

Clearly it is not possible in one test to correctly scale the inertia, viscous and surface tension forces.

In the case of model tests involving ship resistance and powering, this dilemma arising from the inability to test at both Froude scaled and Reynolds scaled speed was resolved by establishing calculated corrections to Froude Scaled model tests which account for the discrepancy in ship and model Reynolds number and viscous forces. This correction was based upon a thorough understanding of the basic viscous phenomena involved, extensive specialized model tests, and on carefully conducted comparisons between model predictions (with the Rn corrections) and ship trials data. Surface tension has very little effect on resistance and powering tests. Even after decades of development and use there is still technical discussion about the details of this model to ship powering extrapolation method.

In contrast, oil spill model testing is in its infancy. The physical oil loss mechanism is very complex and not well understood. There is no "standard" oil loss test and more importantly a correlation between model predicted and actual ship oil loss has not yet been established.

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